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Jacobson

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(54) **LEADLESS CARDIAC PACEMAKER SYSTEM
WITH CONDUCTIVE COMMUNICATION**

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See application file for complete search history.

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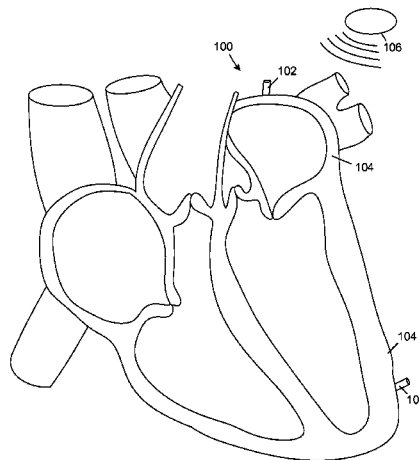
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(57) **ABSTRACT**

A cardiac pacing system comprises multiple leadless cardiac
pacemakers configured for implantation in electrical contact
with a cardiac chamber and configured for multi-chamber
cardiac pacing. The individual leadless cardiac pacemakers
comprise at least two leadless electrodes configured for deliver-
ing cardiac pacing pulses, sensing evoked and/or natural
cardiac electrical signals, and communicating bidirectionally
among the leadless cardiac pacemaker plurality.

27 Claims, 14 Drawing Sheets



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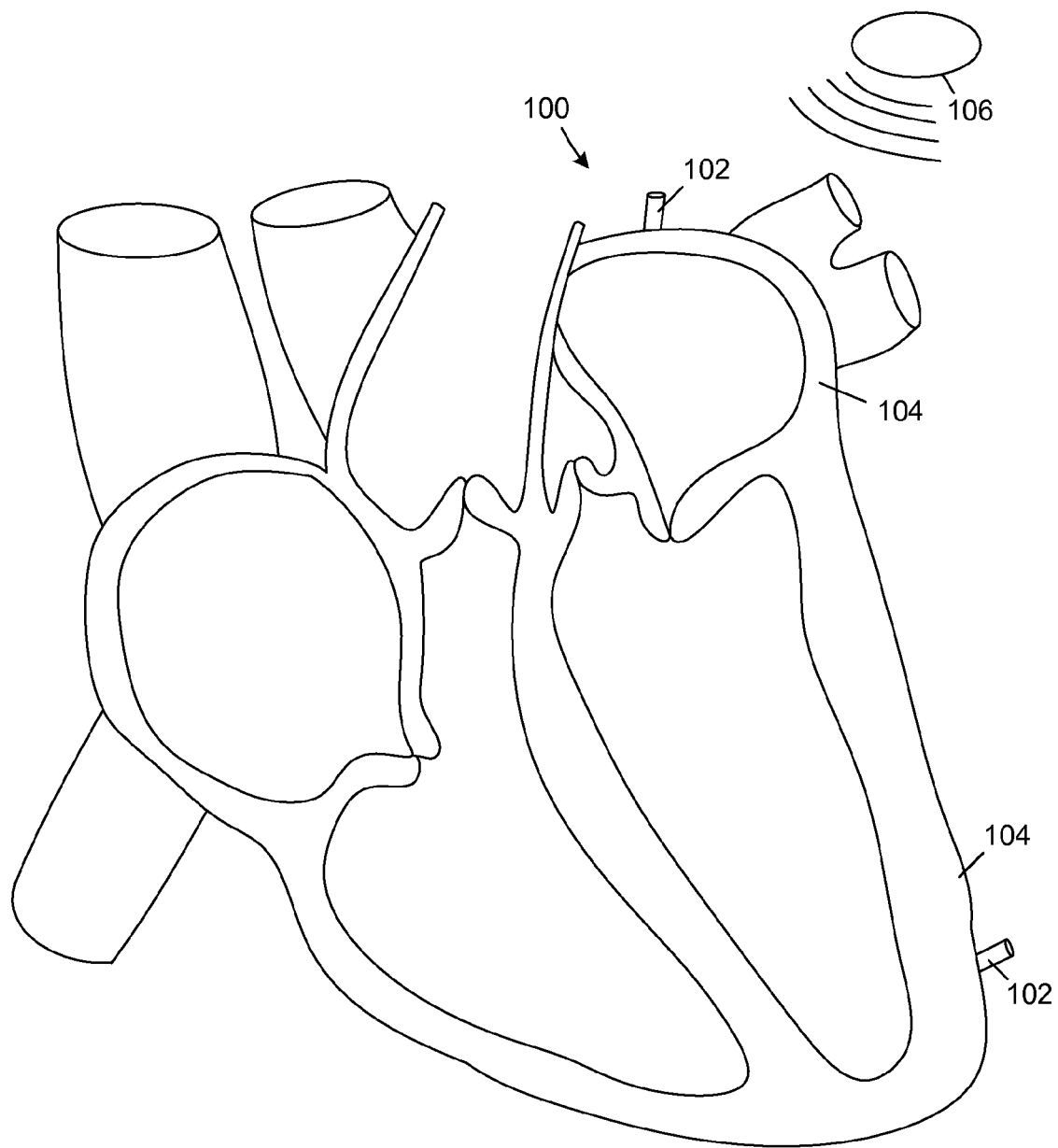


FIG. 1A

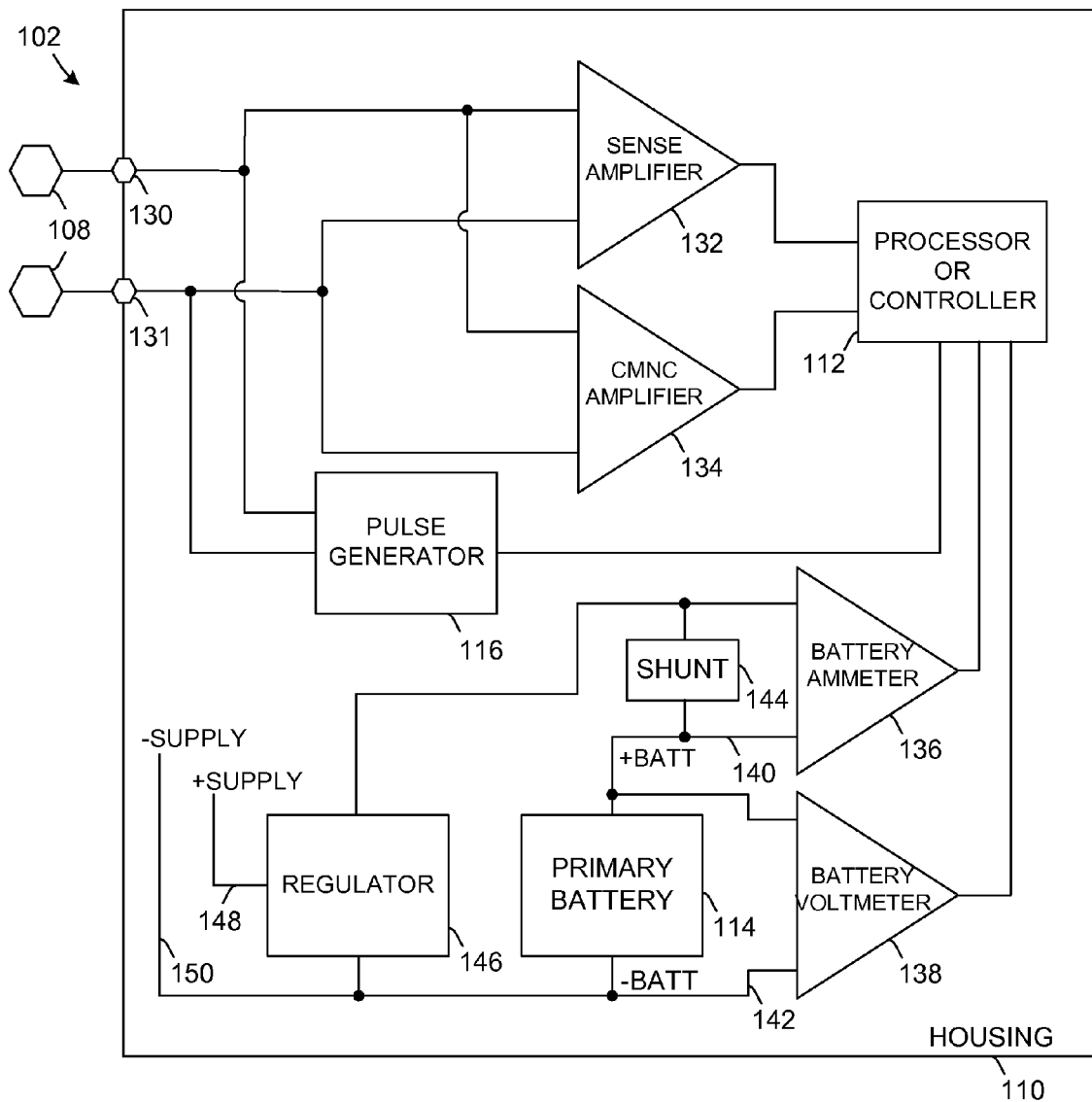


FIG. 1B

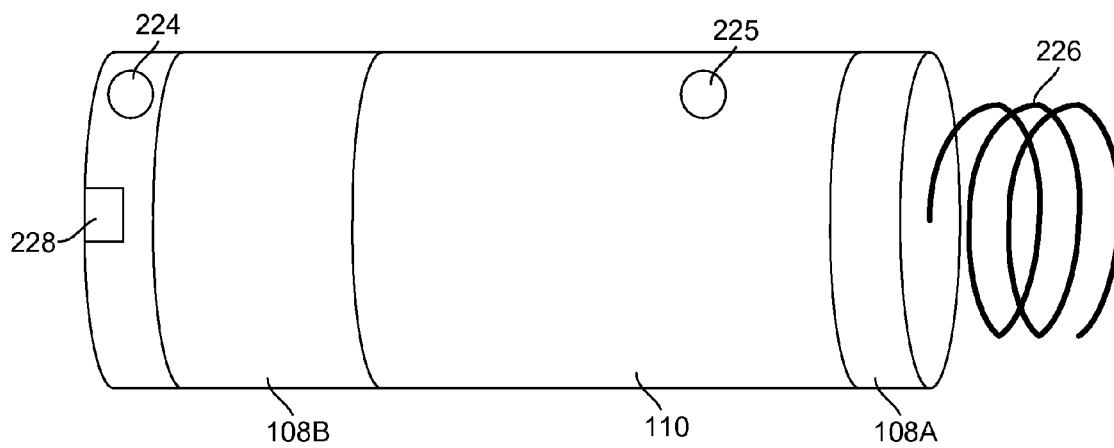


FIG. 2

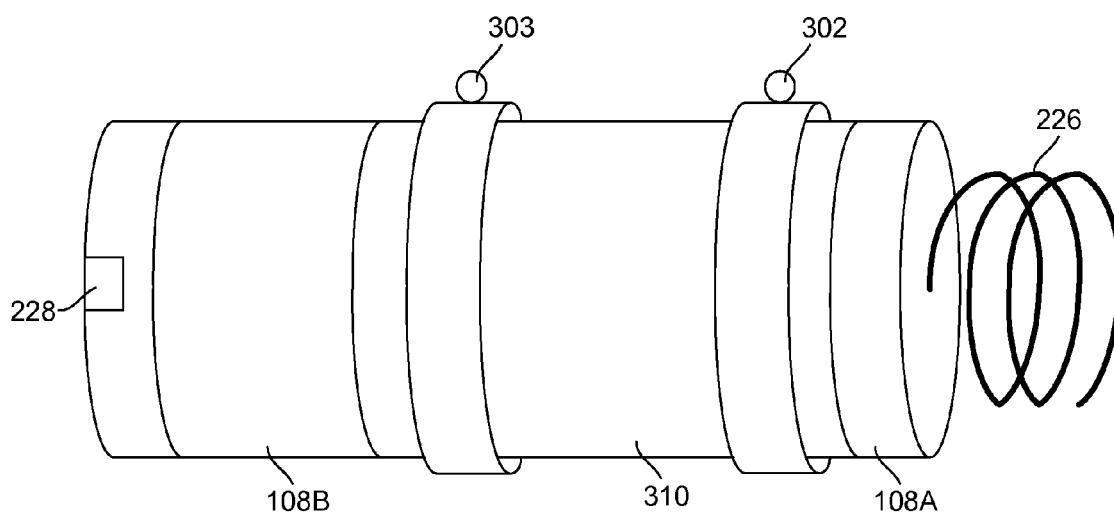
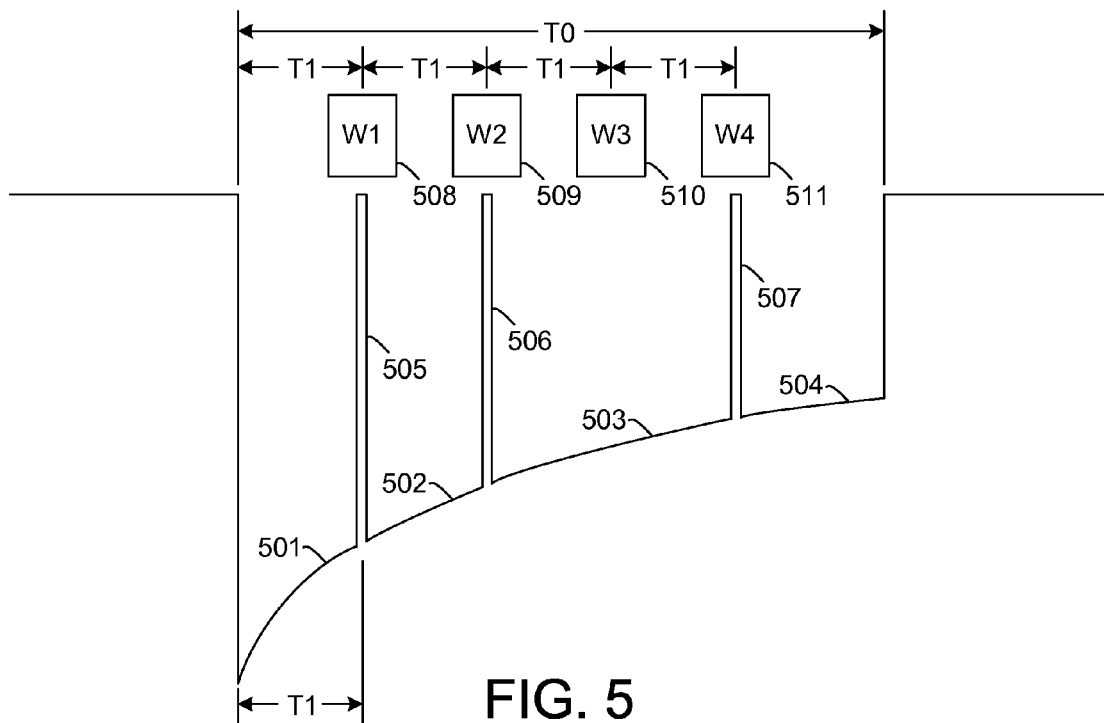
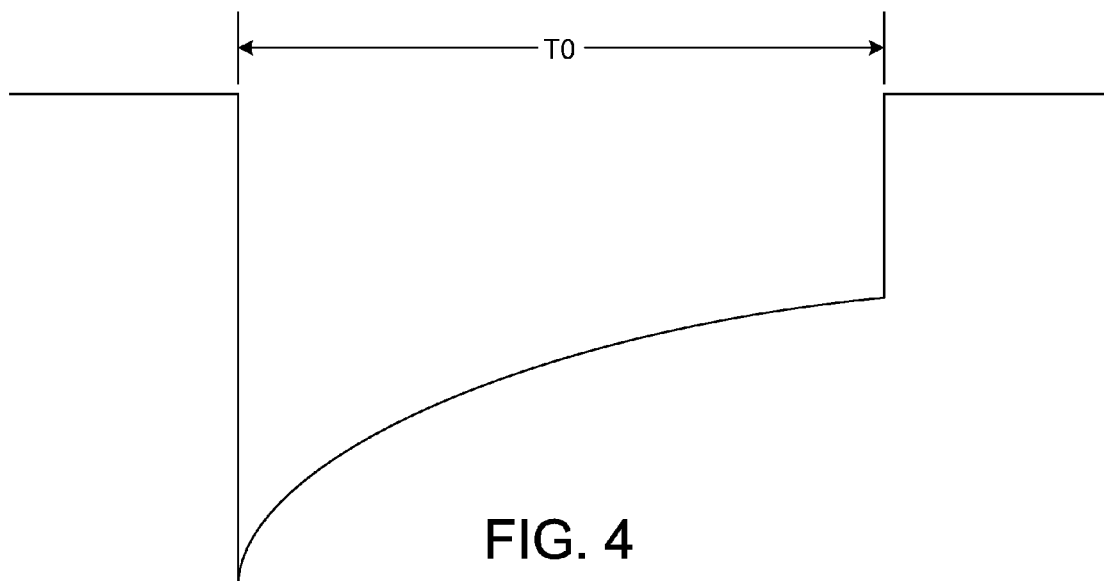


FIG. 3



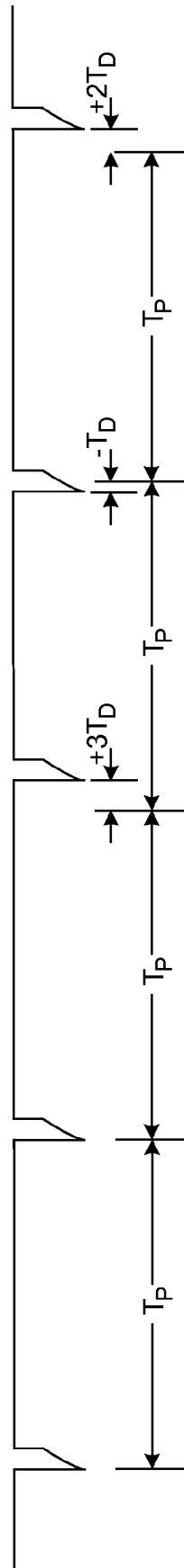


FIG. 6

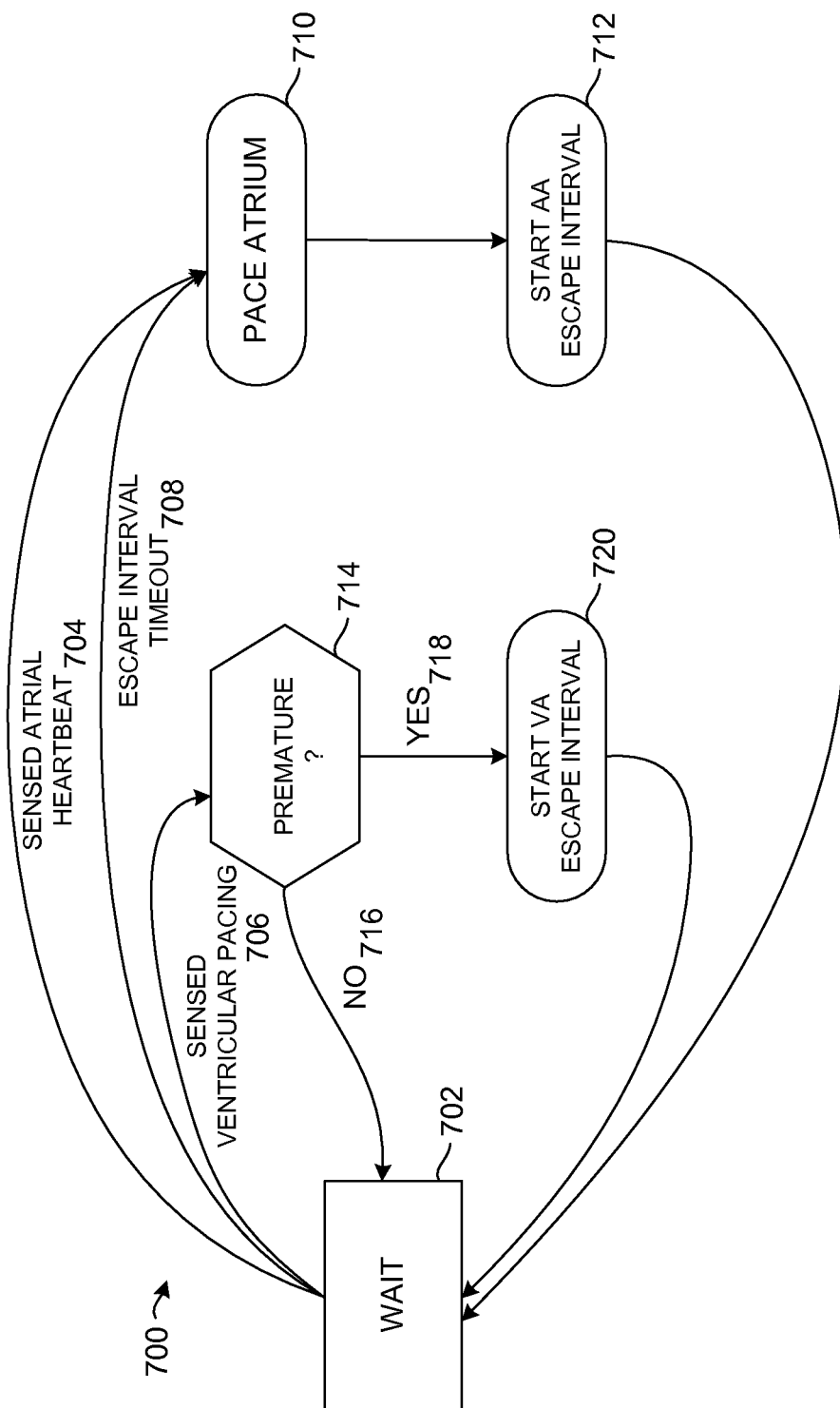


FIG. 7

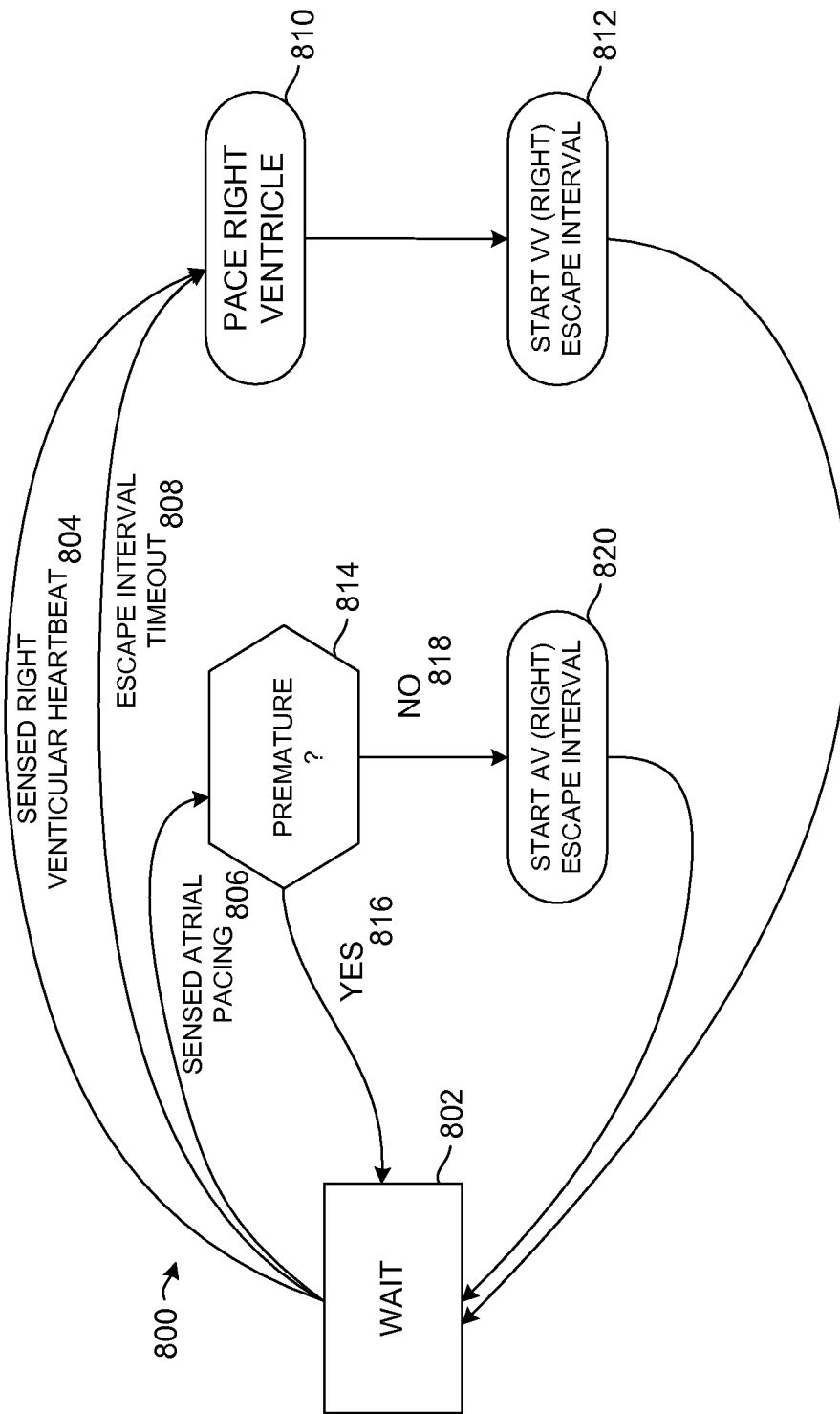


FIG. 8

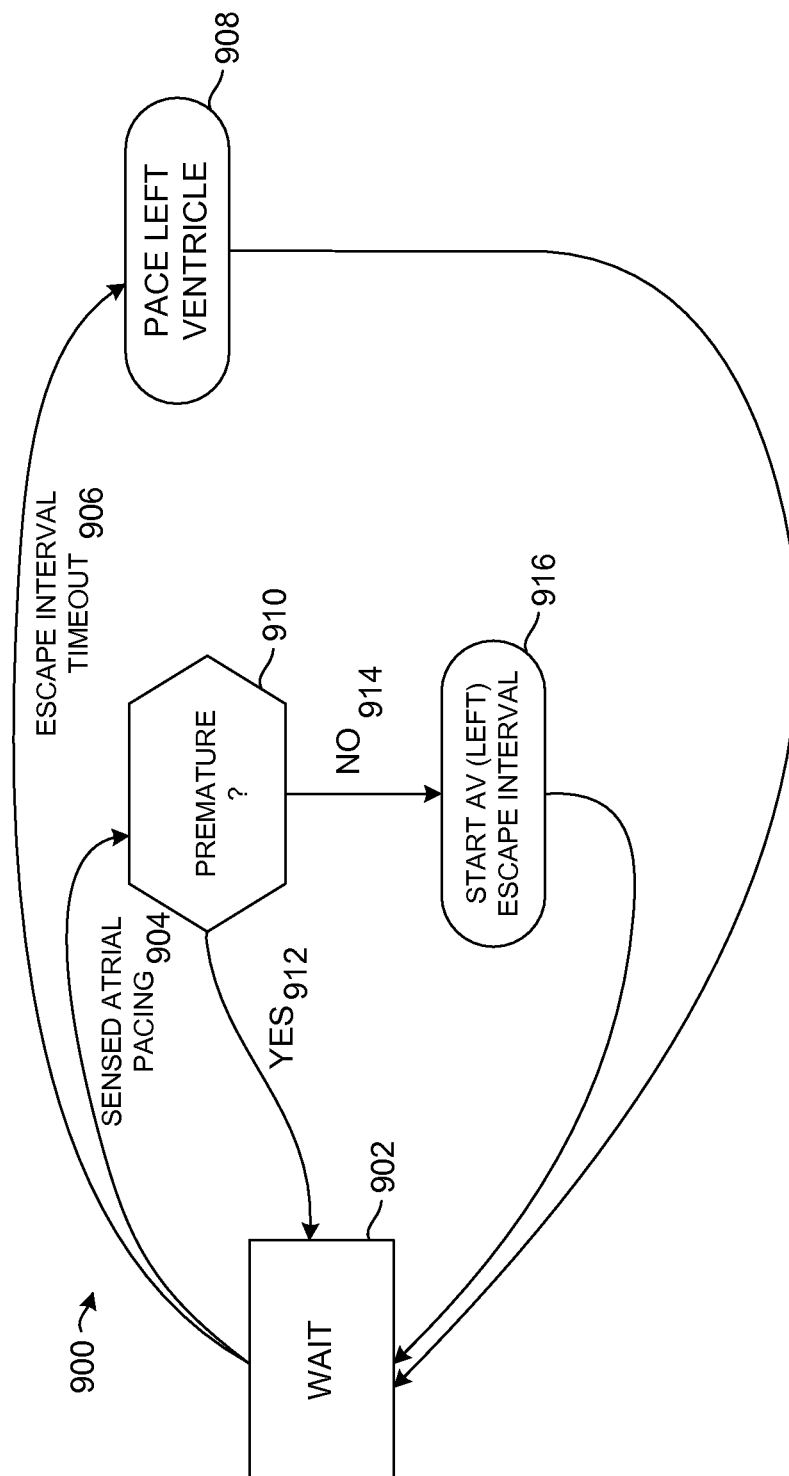


FIG. 9

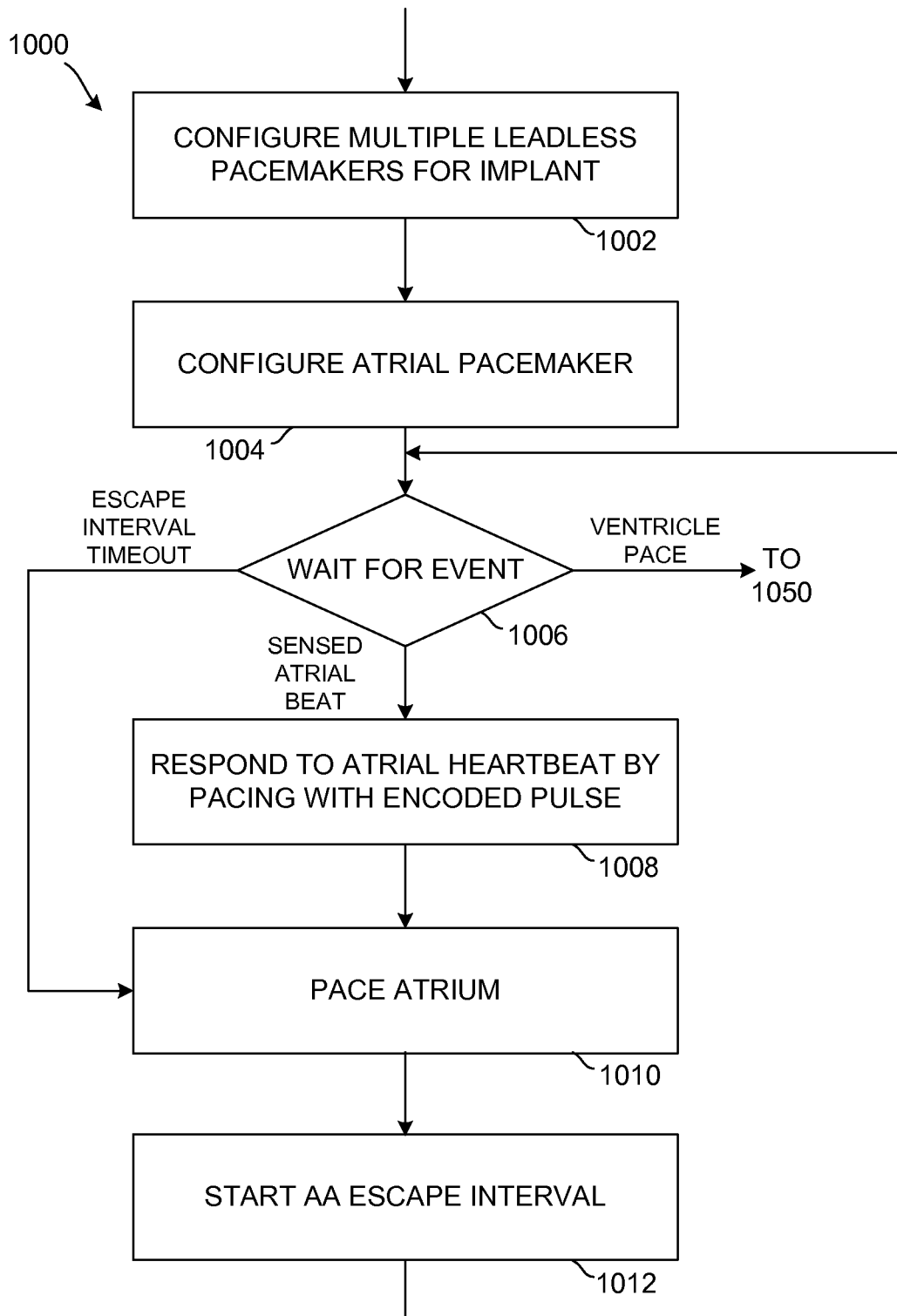
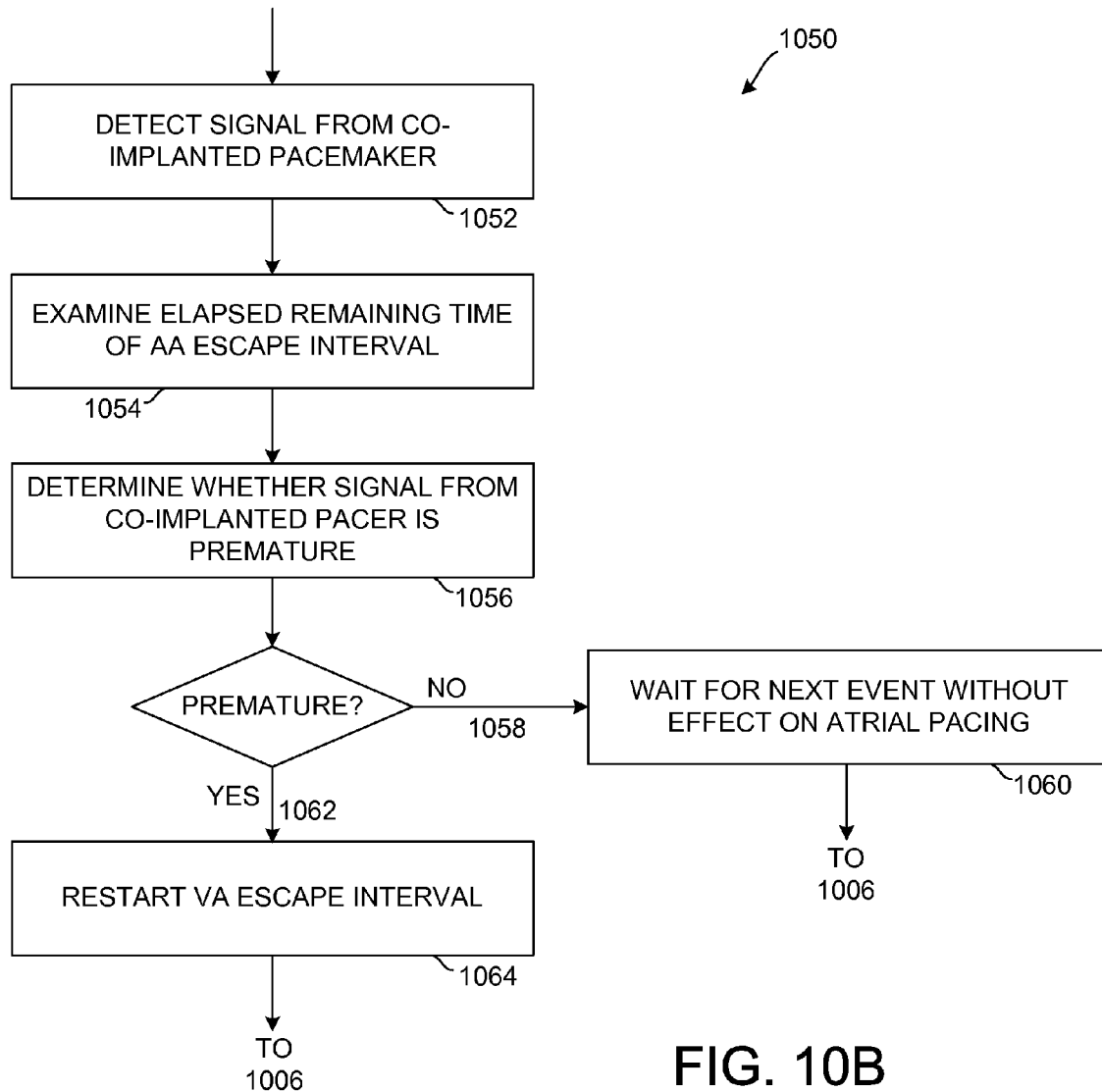


FIG. 10A



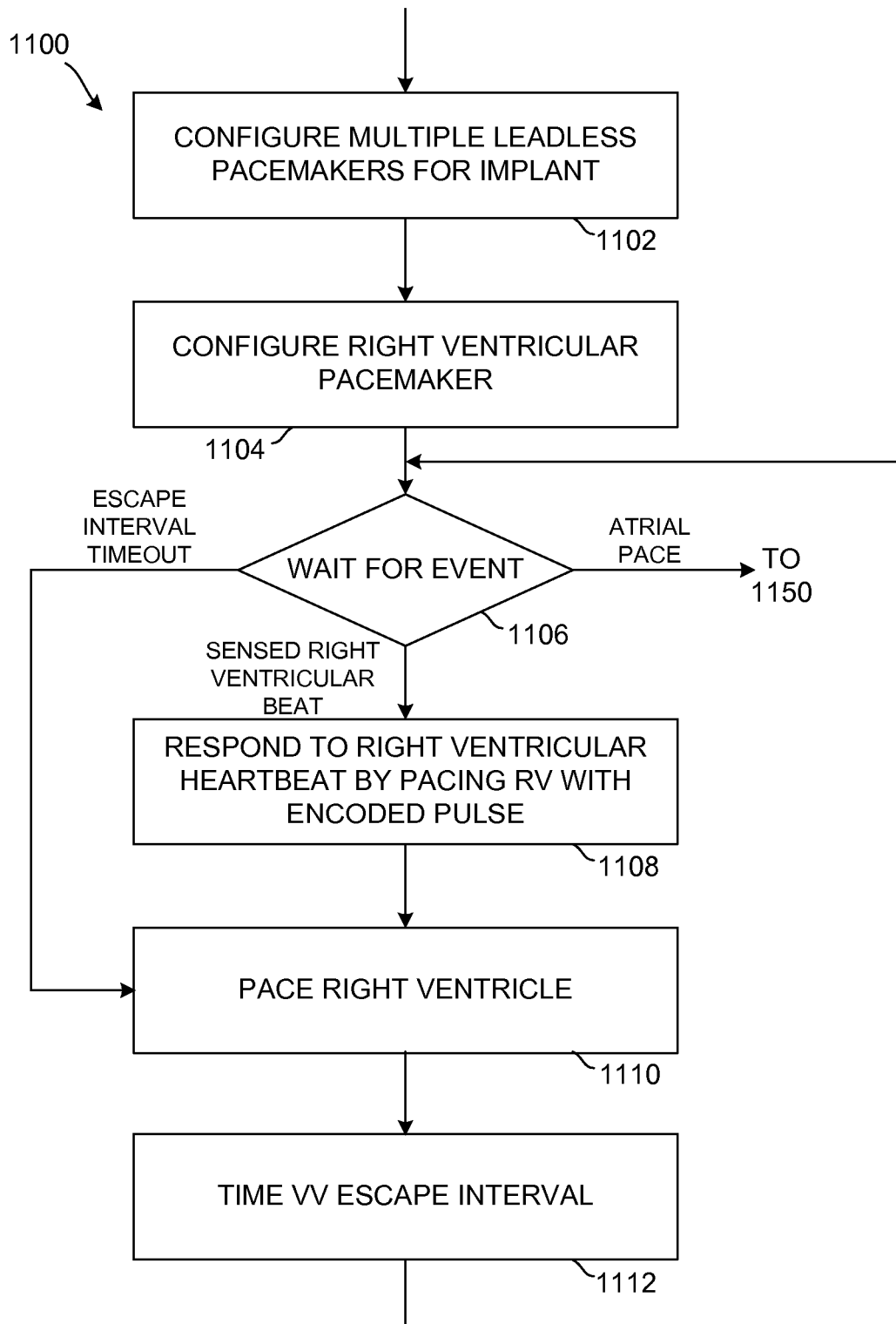


FIG. 11A

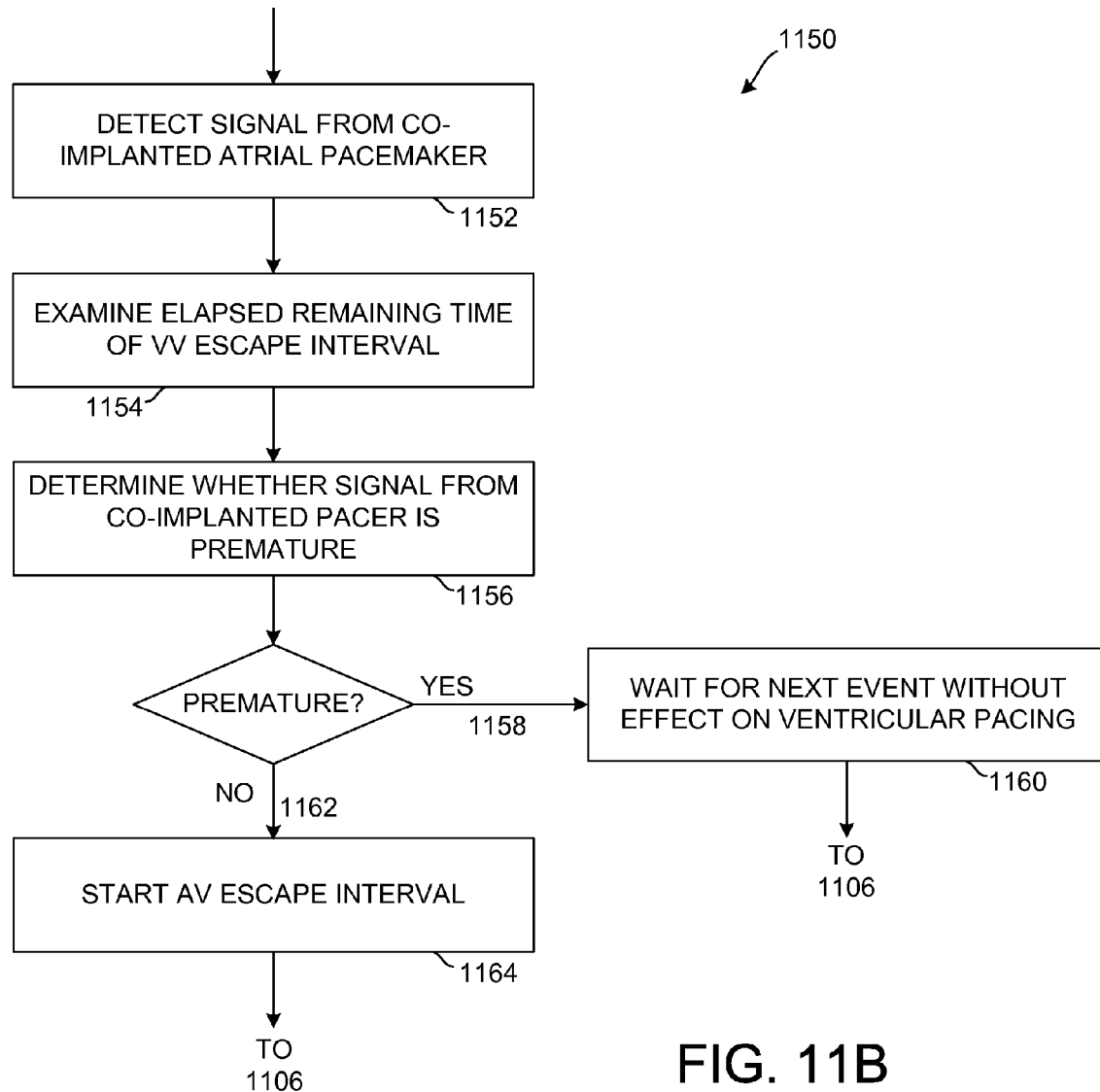


FIG. 11B

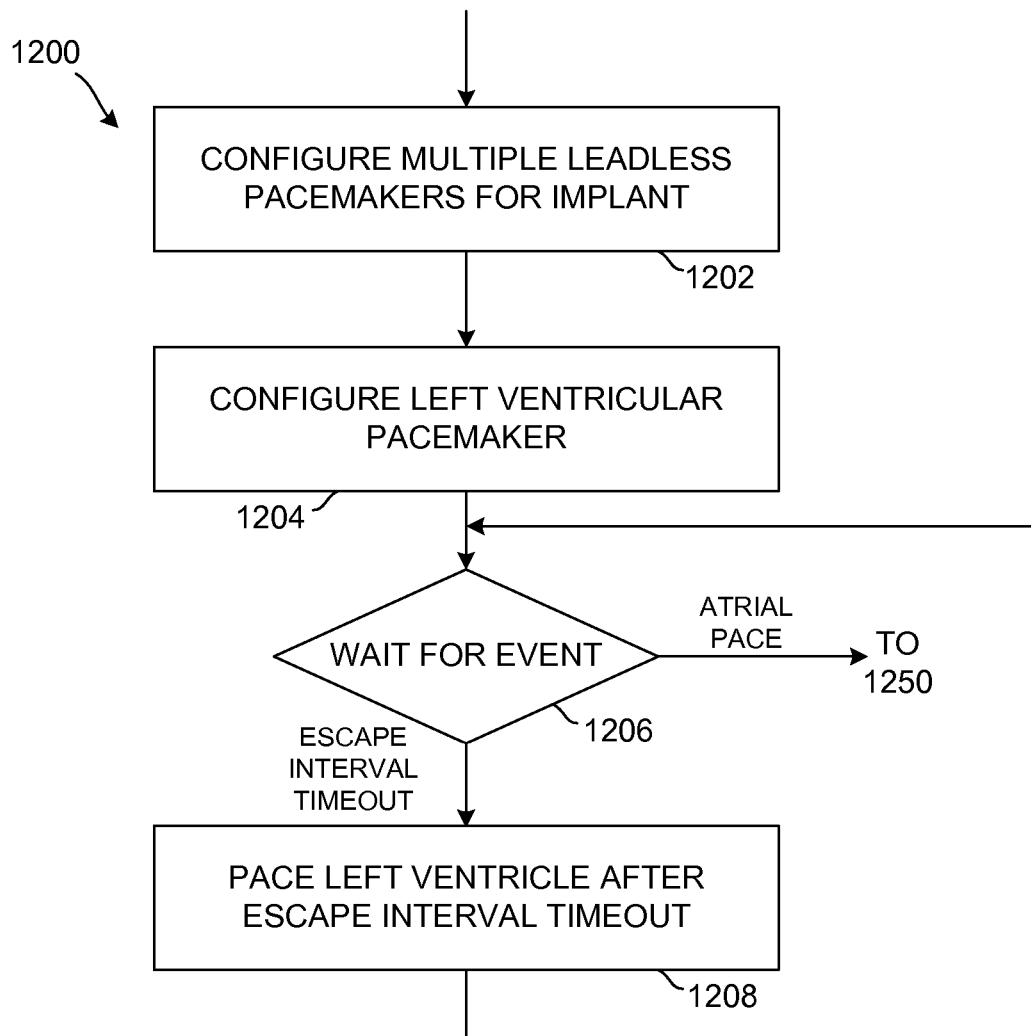


FIG. 12A

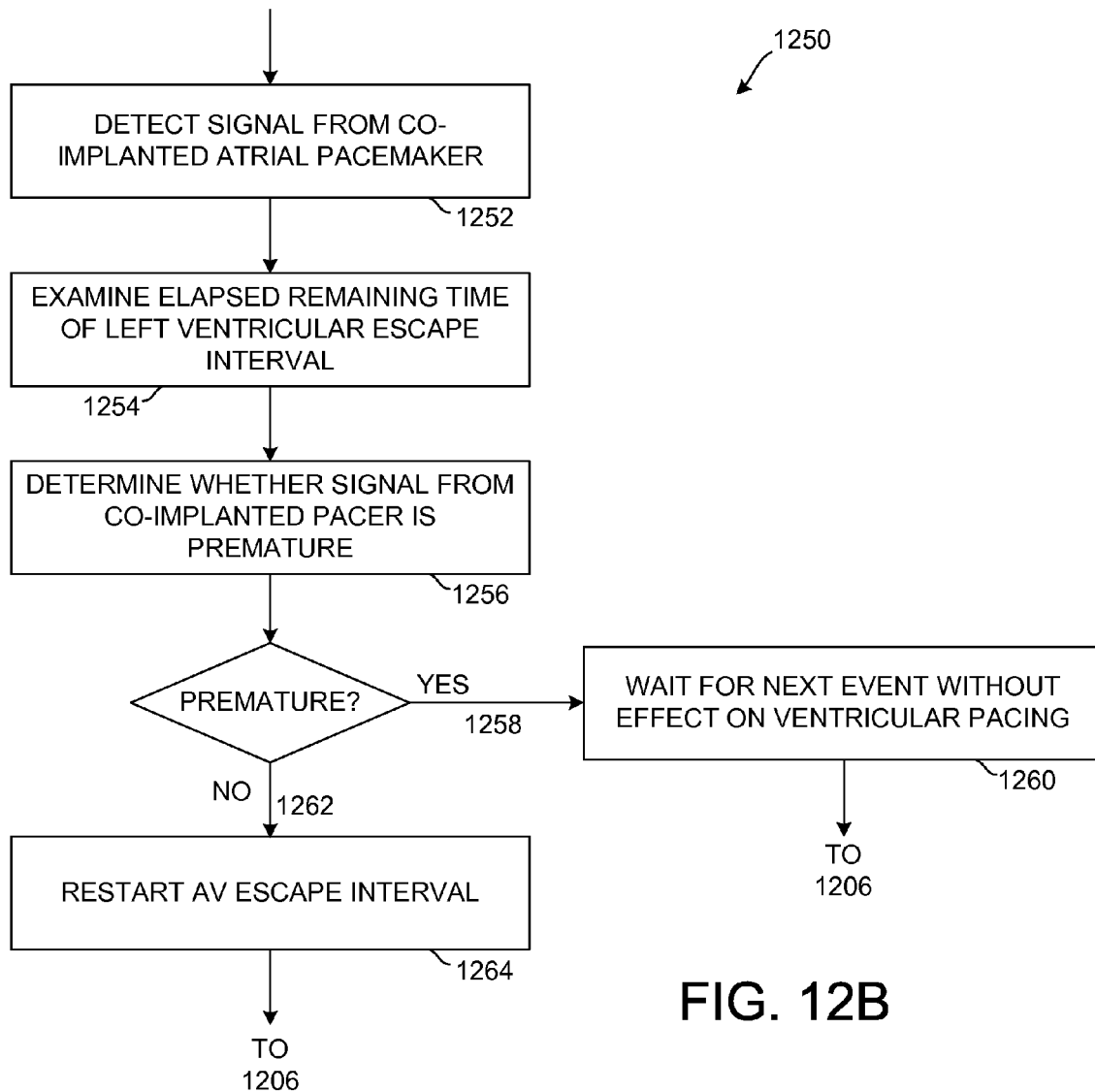


FIG. 12B

LEADLESS CARDIAC PACEMAKER SYSTEM WITH CONDUCTIVE COMMUNICATION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of priority to and incorporates herein by reference in its entirety for all purposes, Provisional U.S. Patent Application Nos.: 60/726,706 entitled "LEADLESS CARDIAC PACEMAKER WITH CONDUCTED COMMUNICATION," filed Oct. 14, 2005; 60/761,531 entitled "LEADLESS CARDIAC PACEMAKER DELIVERY SYSTEM," filed Jan. 24, 2006; 60/729,671 entitled "LEADLESS CARDIAC PACEMAKER TRIGGERED BY CONDUCTED COMMUNICATION," filed Oct. 24, 2005; 60/737,296 entitled "SYSTEM OF LEADLESS CARDIAC PACEMAKERS WITH CONDUCTED COMMUNICATION," filed Nov. 16, 2005; 60/739,901 entitled "LEADLESS CARDIAC PACEMAKERS WITH CONDUCTED COMMUNICATION FOR USE WITH AN IMPLANTABLE CARDIOVERTER-DEFIBRILLATOR," filed Nov. 26, 2005; 60/749,017 entitled "LEADLESS CARDIAC PACEMAKER WITH CONDUCTED COMMUNICATION AND RATE RESPONSIVE PACING," filed Dec. 10, 2005; and 60/761,740 entitled "PROGRAMMER FOR A SYSTEM OF LEADLESS CARDIAC PACEMAKERS WITH CONDUCTED COMMUNICATION," filed Jan. 24, 2006; all by Peter M. Jacobson.

BACKGROUND

Cardiac pacing electrically stimulates the heart when the heart's natural pacemaker and/or conduction system fails to provide synchronized atrial and ventricular contractions at appropriate rates and intervals for a patient's needs. Such bradycardia pacing provides relief from symptoms and even life support for hundreds of thousands of patients. Cardiac pacing may also give electrical overdrive stimulation intended to suppress or convert tachyarrhythmias, again supplying relief from symptoms and preventing or terminating arrhythmias that could lead to sudden cardiac death.

Cardiac pacing is usually performed by a pulse generator implanted subcutaneously or sub-muscularly in or near a patient's pectoral region. The generator usually connects to the proximal end of one or more implanted leads, the distal end of which contains one or more electrodes for positioning adjacent to the inside or outside wall of a cardiac chamber. The leads have an insulated electrical conductor or conductors for connecting the pulse generator to electrodes in the heart. Such electrode leads typically have lengths of 50 to 70 centimeters.

A conventional pulse generator may be connected to more than one electrode-lead. For example, atrio-ventricular pacing, also commonly called dual-chamber pacing, involves a single pulse generator connected to one electrode-lead usually placed in the right atrium and a second electrode-lead usually placed in the right ventricle. Such a system can electrically sense heartbeat signals and deliver pacing pulses separately in each chamber. In typical use, the dual-chamber pacing system paces the atrium if no atrial heartbeat is sensed since a predetermined time, and then paces the ventricle if no ventricular heartbeat is sensed within a predetermined time after the natural or paced atrial beat. Such pulse generators can also alter the timing of atrial and ventricular pacing pulses when sensing a ventricular beat that is not preceded by an atrial beat within a predetermined time; that is, a ventricular ectopic beat or premature ventricular contraction. Conse-

quently, dual-chamber pacing involves pacing and sensing in an atrium and a ventricle, and internal communication element so that an event in either chamber can affect timing of pacing pulses in the other chamber.

Recently, left-ventricular cardiac pacing has been practiced to ameliorate heart failure; a practice termed cardiac resynchronization therapy (CRT). CRT has been practiced with electrode-leads and a pulse generator, either an implantable cardioverter-defibrillator (CRT-D) or an otherwise conventional pacemaker (CRT-P). The left-ventricular pacing conventionally uses an electrode in contact with cardiac muscle in that chamber. The corresponding electrode-lead is usually placed endocardially in a transvenous manner through the coronary sinus vein, or epicardially. Left-ventricular pacing is usually practiced together with right-atrial and right-ventricular pacing with a single implanted pulse generator connected to three electrode-leads. CRT pulse generators can independently vary the time between an atrial event and right-ventricular pacing, and the time between an atrial event and left-ventricular pacing, so that the left ventricular pacing pulse can precede, follow, or occur at the same time as the right-ventricular pacing pulse. Similarly to dual-chamber pacing, systems with left-ventricular pacing also change atrial and ventricular pacing timing in response to premature ventricular contractions. Consequently, CRT-D or CRT-P involves pacing in an atrium and in two ventricles, sensing in the atrium and at least one ventricle, and an internal communication element so that an event in the atrium can affect timing of pacing pulses in each ventricle, and an internal communication element so that an event in at least one ventricle can affect timing of pacing pulses in the atrium and the other ventricle.

Pulse generator parameters are usually interrogated and modified by a programming device outside the body, via a loosely-coupled transformer with one inductance within the body and another outside, or via electromagnetic radiation with one antenna within the body and another outside.

Although tens of thousands of dual-chamber and CRT systems are implanted annually, several problems are known.

The pulse generator, when located subcutaneously, presents a bulge in the skin that patients can find unsightly or unpleasant. Patients can manipulate or "twiddle" the device. Even without persistent twiddling, subcutaneous pulse generators can exhibit erosion, extrusion, infection, and disconnection, insulation damage, or conductor breakage at the wire leads. Although sub-muscular or abdominal placement can address some of these concerns, a more difficult surgical procedure is involved for implantation and adjustment, which can prolong patient recovery.

A conventional pulse generator, whether pectoral or abdominal, has an interface for connection to and disconnection from the electrode leads that carry signals to and from the heart. Usually at least one male connector molding has at least one terminal pin at the proximal end of the electrode lead. The at least one male connector mates with at least one corresponding female connector molding and terminal block within the connector molding at the pulse generator. Usually a setscrew is threaded in at least one terminal block per electrode lead to secure the connection electrically and mechanically. One or more O-rings usually are also supplied to help maintain electrical isolation between the connector moldings. A setscrew cap or slotted cover is typically included to provide electrical insulation of the setscrew. The complex connection between connectors and leads provides multiple opportunities for malfunction.

For example, failure to introduce the lead pin completely into the terminal block can prevent proper connection between the generator and electrode.

Failure to insert a screwdriver correctly through the setscrew slot, causing damage to the slot and subsequent insulation failure.

Failure to engage the screwdriver correctly in the setscrew can cause damage to the setscrew and preventing proper connection.

Failure to tighten the setscrew adequately also can prevent proper connection between the generator and electrode, however over-tightening of the setscrew can cause damage to the setscrew, terminal block, or lead pin, and prevent disconnection if necessary for maintenance.

Fluid leakage between the lead and generator connector moldings, or at the setscrew cover, can prevent proper electrical isolation.

Insulation or conductor breakage at a mechanical stress concentration point where the lead leaves the generator can also cause failure.

Inadvertent mechanical damage to the attachment of the connector molding to the generator can result in leakage or even detachment of the molding.

Inadvertent mechanical damage to the attachment of the connector molding to the lead body, or of the terminal pin to the lead conductor, can result in leakage, an open-circuit condition, or even detachment of the terminal pin and/or molding.

The lead body can be cut inadvertently during surgery by a tool, or cut after surgery by repeated stress on a ligature used to hold the lead body in position. Repeated movement for hundreds of millions of cardiac cycles can cause lead conductor breakage or insulation damage anywhere along the lead body.

Although leads are available commercially in various lengths, in some conditions excess lead length in a patient exists and is to be managed. Usually the excess lead is coiled near the pulse generator. Repeated abrasion between the lead body and the generator due to lead coiling can result in insulation damage to the lead.

Friction of the lead against the clavicle and the first rib, known as subclavian crush, can result in damage to the lead.

In dual-chamber pacing and CRT, multiple leads are implanted in the same patient and sometimes in the same vessel. Abrasion between these leads for hundreds of millions of cardiac cycles can cause insulation breakdown or even conductor failure.

Communication between the implanted pulse generator and external programmer uses a telemetry coil or antenna and associated circuitry in the pulse generator where complexity increases the size and cost of the devices. Moreover, power necessary from the pulse generator battery for communication typically exceeds power for pacing by one or more orders of magnitude, introducing a requirement for battery power capability that can prevent selecting the most optimal battery construction for the otherwise low-power requirements of pacing.

SUMMARY

According to an embodiment of a cardiac pacing system, multiple leadless cardiac pacemakers are configured for implantation in electrical contact with a cardiac chamber and configured for multi-chamber cardiac pacing. The individual leadless cardiac pacemakers comprise at least two leadless electrodes configured for delivering cardiac pacing pulses,

sensing evoked and/or natural cardiac electrical signals, and communicating bidirectionally among the leadless cardiac pacemaker plurality.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention relating to both structure and method of operation may best be understood by referring to the following description and accompanying drawings, in which similar reference characters denote similar elements throughout the several views:

FIG. 1A is a pictorial diagram showing an embodiment of a cardiac pacing system including multiple leadless cardiac pacemakers that can be used in combination for multi-chamber cardiac pacing using conductive communication;

FIG. 1B is a schematic block diagram showing interconnection of operating elements of an embodiment of a leadless cardiac pacemaker that can be used in the multi-chamber cardiac pacing system;

FIG. 2 is a pictorial diagram showing the physical location of some elements of an embodiment of a leadless biostimulator that can be used as part of a multi-chamber cardiac pacing system;

FIG. 3 is a pictorial diagram that depicts the physical location of some elements in an alternative embodiment of a leadless biostimulator that can be used as part of a multi-chamber cardiac pacing system;

FIG. 4 is a time waveform graph illustrating a conventional pacing pulse;

FIG. 5 is a time waveform graph depicting a pacing pulse adapted for communication as implemented for an embodiment of the illustrative pacing system;

FIG. 6 is a time waveform graph showing a sample pulse waveform using off-time variation for communication;

FIG. 7 is a state-mechanical representation illustrating an embodiment of a technique for operation of an atrial leadless cardiac pacemaker in a multi-chamber cardiac pacing system;

FIG. 8 is a state-mechanical representation illustrating an embodiment of a technique for operation of a right-ventricular leadless cardiac pacemaker in a multi-chamber cardiac pacing system;

FIG. 9 is a state-mechanical representation illustrating an embodiment of a technique for operation of a left-ventricular leadless cardiac pacemaker in a multi-chamber cardiac pacing system;

FIGS. 10A and 10B are schematic flow charts that depict embodiments of methods for operating an atrial leadless cardiac pacemaker in multi-chamber cardiac pacing;

FIGURES 11A and 11B are schematic flow charts that depict embodiments of methods for operating an right-ventricular leadless cardiac pacemaker in multi-chamber cardiac pacing; and

FIGS. 12A and 12B are schematic flow charts that depict embodiments of methods for operating a left-ventricular leadless cardiac pacemaker in multi-chamber cardiac pacing.

DETAILED DESCRIPTION

A system of leadless cardiac pacemakers with low-power conducted communication enables dual-chamber pacing, CRT-P, or other multi-chamber pacing.

Various embodiments of a system of leadless cardiac pacemakers with conducted communication for multi-chamber pacing are disclosed that can implement, for example, dual-chamber pacing or three-chamber pacing for cardiac resynchronization therapy. The individual leadless cardiac pacemakers can be substantially enclosed in a hermetic housing

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suitable for placement on or attachment to the inside or outside of a cardiac chamber. The pacemaker can have at least two electrodes located within, on, or near the housing, for delivering pacing pulses to and sensing electrical activity from the muscle of the cardiac chamber, and for bidirectional communication with at least one other co-implanted leadless cardiac pacemaker and optionally with another device outside the body. The housing can contain a primary battery to provide power for pacing, sensing, and communication. The housing can also contain circuits for sensing cardiac activity from the electrodes, receiving information from at least one other device via the electrodes, generating pacing pulses for delivery via the electrodes, transmitting information to at least one other device via the electrodes, monitoring device health, and controlling these operations in a predetermined manner.

A cardiac pacing system includes two or more leadless cardiac pacemakers to enable improved performance in comparison to conventional multi-chamber cardiac pacing arrangements.

In some embodiments, a cardiac pacing system comprises two or more leadless pacemakers for implantation adjacent to the inside or outside wall of a cardiac chamber, without the need for a connection between the pulse generator and electrode lead that can be connected or disconnected during implantation and repair procedures, and without the need for a lead body.

In some embodiments of a cardiac pacing system, communication between implanted leadless cardiac pacemakers and optionally between an implanted leadless cardiac pacemaker and a device external to the body, uses conducted communication via the same electrodes used for pacing, without the need for an antenna or telemetry coil.

Some embodiments and/or arrangements can implement communication between an implanted leadless cardiac pacemaker and a device or devices internal or external to the body, with power requirements similar to those for cardiac pacing, to enable optimization of battery performance. For example, transmission from the leadless cardiac pacemaker adds no power while reception adds a limited amount of power, such as about 25 microwatts.

Referring to FIG. 1A, a pictorial diagram, which is not to scale, shows an embodiment of a cardiac pacing system **100** including multiple leadless cardiac pacemakers **102** that can be used in combination for multi-chamber cardiac pacing and can communicate via conductive communication. FIG. 1B is a schematic block diagram showing an embodiment of a leadless cardiac pacemaker **102** that can be a component of the cardiac pacing system **100**. In the system **100**, multiple leadless cardiac pacemakers **102** are individually configured for implantation in electrical contact with multiple cardiac chambers **104** and arranged in combination for multi-chamber cardiac pacing. The individual leadless cardiac pacemakers **102** comprise two or more leadless electrodes **108** configured for delivering cardiac pacing pulses, sensing evoked and/or natural cardiac electrical signals, and communicating bidirectionally among the leadless cardiac pacemakers.

The illustrative cardiac pacing system **100** enables extended performance in comparison to conventional dual-chamber cardiac pacing and cardiac resynchronization therapy (CRT-P). The depicted cardiac pacing system **100** can be configured for dual-chamber, CRT-P, and other multi-chamber cardiac pacing schemes.

Individual pacemakers of the multiple leadless cardiac pacemakers **102** can comprise a hermetic housing **110** configured for placement on or attachment to the inside or outside of the cardiac chambers **104**. The two or more leadless elec-

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trodes **108** proximal to the housing **110** can be configured for bidirectional communication with one or more other devices **106** within or outside the body.

The cardiac pacing system **100** can perform multi-chamber cardiac pacing in the absence of a pulse generator located in the pectoral region or abdomen of a patient, in the absence of an electrode-lead separate from the pulse generator, in the absence of a communication coil or antenna, and without imposing an additional requirement on battery power for communication of pacing pulse delivery.

The cardiac pacing system **100** attains improved performance through usage of at least two leadless cardiac pacemakers **102**. An individual leadless cardiac pacemaker **102** can be substantially enclosed in a hermetic housing **110** which is suitable for placement on or attachment to the inside or outside of a cardiac chamber **104**. The pacemaker **102** has at least two electrodes **108** located within, on, or near the housing **110**, for delivering pacing pulses to and sensing electrical activity from the muscle of the cardiac chamber **104**, and for bidirectional communication with at least one other leadless cardiac pacemaker within the body, and possibly for bidirectional communication with at least one other device **106** outside the body. The illustrative housing **110** contains a primary battery **114** to supply power for pacing, sensing, and communication. The depicted housing **110** also contains circuits for sensing cardiac activity from the electrodes, receiving information from at least one other device via the electrodes **108**, generating pacing pulses for delivery via the electrodes **108**, transmitting information to at least one other device via the electrodes **108**, optionally monitoring device health, and controlling the operations in a predetermined manner.

FIG. 1B depicts a single leadless cardiac pacemaker **102** and shows the pacemaker's functional elements substantially enclosed in a hermetic housing **110**. The pacemaker **102** has at least two electrodes **108** located within, on, or near the housing **110**, for delivering pacing pulses to and sensing electrical activity from the muscle of the cardiac chamber, and for bidirectional communication with at least one other device within or outside the body. Hermetic feedthroughs **130**, **131** conduct electrode signals through the housing **110**. The housing **110** contains a primary battery **114** to supply power for pacing, sensing, and communication. The housing **110** also contains circuits **132** for sensing cardiac activity from the electrodes **108**, circuits **134** for receiving information from at least one other device via the electrodes **108**, and a pulse generator **116** for generating pacing pulses for delivery via the electrodes **108** and also for transmitting information to at least one other device via the electrodes **108**. The housing **110** can further contain circuits for monitoring device health, for example a battery current monitor **136** and a battery voltage monitor **138**, and can contain circuits **112** for controlling operations in a predetermined manner.

Individual pacemakers **102** of the leadless cardiac pacemaker plurality can be configured to intercommunicate and to communicate with a non-implanted programmer via the electrodes **108** that are also used for delivering pacing pulses. Accordingly, the pacemakers **102** can be configured for antenna-less and telemetry coil-less communication. The individual pacemakers **102** can also intercommunicate among multiple pacemakers and communicate with a non-implanted programmer via communication that has outgoing communication power requirements essentially met by power consumed in cardiac pacing.

The two or more leadless electrodes **108** can be configured to communicate bidirectionally among the multiple leadless cardiac pacemakers to coordinate pacing pulse delivery using

messages that identify an event at an individual pacemaker originating the message. A pacemaker or pacemakers that receive the message react as directed by the message depending on the message origin or location. In some embodiments or conditions, the two or more leadless electrodes **108** can be configured to communicate bidirectionally among the multiple leadless cardiac pacemakers and transmit data including designated codes for events detected or created by an individual pacemaker. Individual pacemakers can be configured to issue a unique code corresponding to an event type and a location of the sending pacemaker.

Information communicated on the incoming communication channel can include but is not limited to pacing rate, pulse duration, sensing threshold, and other parameters commonly programmed externally in conventional pacemakers. Information communicated on the outgoing communication channel can include but is not limited to programmable parameter settings, pacing and sensing event counts, battery voltage, battery current, device health, and other information commonly displayed by external programmers used with conventional pacemakers. The outgoing communication channel can also echo information from the incoming channel, to confirm correct programming.

Moreover, information communicated on the incoming channel can also include a message from another leadless cardiac pacemaker signifying that the other leadless cardiac pacemaker has sensed a heartbeat or has delivered a pacing pulse, and identifies the location of the other pacemaker. Similarly, information communicated on the outgoing channel can also include a message to another leadless cardiac pacemaker or pacemakers that the sending leadless cardiac pacemaker has sensed a heartbeat or has delivered a pacing pulse at the location of the sending pacemaker.

For example, in some embodiments an individual pacemaker **102** of the multiple leadless cardiac pacemakers can be configured to deliver a coded pacing pulse with a code assigned according to pacemaker location and configured to transmit a message to one or more other leadless cardiac pacemakers via the coded pacing pulse wherein the code identifies the individual pacemaker originating an event. The pacemaker or pacemakers receiving the message are adapted to respond to the message in a predetermined manner depending on type and location of the event.

In some embodiments and in predetermined conditions, an individual pacemaker **102** of the multiple leadless cardiac pacemakers can be configured to communicate to one or more other implanted pacemakers indication of the occurrence of a sensed heartbeat at the individual pacemaker location via generation of a coded pacing pulse triggered by the sensed heartbeat in a natural refractory period following the sensed heartbeat.

Multiple leadless cardiac pacemakers **102** can be configured for co-implantation in a single patient and multiple-chamber pacing, for example by defining logic internal to the pacemakers **102** at manufacture, by programming using an external programmer, or the like. Bidirectional communication among the multiple leadless cardiac pacemakers can be arranged to communicate notification of a sensed heartbeat or delivered pacing pulse event and encoding type and location of the event to another implanted pacemaker or pacemakers. The pacemaker or pacemakers receiving the communication decode the information and respond depending on location of the receiving pacemaker and predetermined system functionality.

Also shown in FIG. 1B, the primary battery **114** has positive terminal **140** and negative terminal **142**. A suitable primary battery has an energy density of at least 3 W·h/cc, a

power output of 70 microwatts, a volume less than 1 cubic centimeter, and a lifetime greater than 5 years.

One suitable primary battery uses beta-voltaic technology, licensed to BetaBatt Inc. of Houston, Tex., USA, and developed under a trade name DECTTM Cell, in which a silicon wafer captures electrons emitted by a radioactive gas such as tritium. The wafer is etched in a three-dimensional surface to capture more electrons. The battery is sealed in a hermetic package which entirely contains the low-energy particles emitted by tritium, rendering the battery safe for long-term human implant from a radiological-health standpoint. Tritium has a half-life of 12.3 years so that the technology is more than adequate to meet a design goal of a lifetime exceeding 5 years.

Current from the positive terminal **140** of primary battery **114** flows through a shunt **144** to a regulator circuit **146** to create a positive voltage supply **148** suitable for powering the remaining circuitry of the pacemaker **102**. The shunt **144** enables the battery current monitor **136** to provide the processor **112** with an indication of battery current drain and indirectly of device health.

The illustrative power supply can be a primary battery **114** such as a beta-voltaic converter that obtains electrical energy from radioactivity. In some embodiments, the power supply can be selected as a primary battery **114** that has a volume less than approximately 1 cubic centimeter.

In an illustrative embodiment, the primary battery **114** can be selected to source no more than 70 microwatts instantaneously since a higher consumption may cause the voltage across the battery terminals to collapse. Accordingly in one illustrative embodiment the circuits depicted in FIG. 1B can be designed to consume no more than a total of 64 microwatts. The design avoids usage of a large filtering capacitor for the power supply or other accumulators such as a supercapacitor or rechargeable secondary cell to supply peak power exceeding the maximum instantaneous power capability of the battery, components that would add volume and cost.

In various embodiments, the system can manage power consumption to draw limited power from the battery, thereby reducing device volume. Each circuit in the system can be designed to avoid large peak currents. For example, cardiac pacing can be achieved by discharging a tank capacitor (not shown) across the pacing electrodes. Recharging of the tank capacitor is typically controlled by a charge pump circuit. In a particular embodiment, the charge pump circuit is throttled to recharge the tank capacitor at constant power from the battery.

Implantable systems that communicate via long distance radio-frequency (RF) schemes, for example Medical Implant Communication Service (MICS) transceivers, which exhibit a peak power specification on the order of 10 milliwatts, and other RF or inductive telemetry schemes are unable to operate without use of an additional accumulator. Moreover, even with the added accumulator, sustained operation would ultimately cause the voltage across the battery to collapse.

Referring to FIG. 2, a schematic pictorial view shows an embodiment of the leadless cardiac pacemaker **102** that can be used with at least one other pacemaker in the cardiac pacing system **100**. The leadless cardiac pacemaker **102** comprises a hermetic housing **110** configured for placement on or attachment to the inside or outside of a cardiac chamber **104**. Two or more electrodes **108** abut or are adjacent to the housing **110**. The electrodes **108** are configured for delivering pacing pulses and receiving triggering signals from the other pulse generator **106**. The electrodes **108** can also sense electrical activity from cardiac chamber muscle.

Furthermore, the electrodes **108** are adapted for bidirectional communication with at least one other device within or outside the body. For example, the leadless pacemaker **102** can be configured to communicate with a non-implanted programmer or one or more implanted pulse generators via the same electrodes **108** that are used for delivering pacing pulses. The illustrative leadless pacemaker **102** is adapted for antenna-less and telemetry coil-less communication. Usage of the electrodes **108** for communication enables the leadless pacemaker **102** to communicate with a non-implanted programmer or one or more implanted pulse generators via communication that adds nothing to power requirements in addition to power requirements for cardiac pacing. For example, transmission from the leadless cardiac pacemaker **102** adds no power while reception adds on the order of 25 microwatts.

The illustrative example avoids usage of radiofrequency (RF) communication to send pacing instructions to remote electrodes on a beat-to-beat basis to cause the remote electrodes to emit a pacing pulse. RF communication involves use of an antenna and modulation/demodulation unit in the remote electrode, which increase implant size significantly. Also, communication of pacing instructions on a beat-to-beat basis increases power requirements for the main body and the remote electrode. In contrast, the illustrative system and stimulator do not require beat-to-beat communication with any controlling main body.

The illustrative leadless pacemaker **102** includes an internal power source that can supply all energy for operations and pulse generation. In contrast, some conventional implanted pulse generators have remote pacing electrodes that receive some or all energy from an energy source through an RF induction technique, an energy transfer scheme that employs a large loop antenna on the remote electrode that increases size significantly. In addition, energy transfer with the RF induction technique is inefficient and is associated with a significant increase in battery size of the energy source. In contrast, the illustrative leadless pacemaker **102** uses an internal battery and does not require energy to be drawn from outside sources. Also in the conventional system, the energy source receives sensing information by RF communication from the remote electrodes and sends pacing instructions to the electrodes on a beat-to-beat basis in a configuration that uses an addressing scheme in which the identity of specific remote pacing electrodes is stored in the energy source memory. The conventional method can also be inefficient due to overhead for transmitting an identification number from/to a generic pacing electrode at implant and/or during sensing. The illustrative leadless pacemaker **102** avoids such overhead through a structure in which pulse generation functionality is independent within a single implantable body.

Another conventional technology uses a system of addressable remote electrodes that stimulate body tissue without requiring a main body to send commands for individual stimulations. The remote electrodes are specified to be of a size and shape suitable for injection rather than for endocardial implantation. A controller can set operating parameters and send the parameters to remote electrodes by addressable communication, enabling the remote electrodes function relatively autonomously while incurring some overhead to controller operations. However, the remote electrodes do not sense or monitor cardiac information and rely on the main body to provide sensing functionality. In contrast, the illustrative leadless pacemaker **102** combines pacing and sensing of intrinsic cardiac activity in a single implantable body.

In some embodiments, the controller **112** in one leadless cardiac pacemaker **102** can access signals on the electrodes **108** and can examine output pulse duration from another

pacemaker for usage as a signature for determining triggering information validity and, for a signature arriving within predetermined limits, activating delivery of a pacing pulse following a predetermined delay of zero or more milliseconds.

The predetermined delay can be preset at manufacture, programmed via an external programmer, or determined by adaptive monitoring to facilitate recognition of the triggering signal and discriminating the triggering signal from noise. In some embodiments or in some conditions, the controller **112** can examine output pulse waveform from another leadless cardiac pacemaker for usage as a signature for determining triggering information validity and, for a signature arriving within predetermined limits, activating delivery of a pacing pulse following a predetermined delay of zero or more milliseconds.

The illustrative leadless pacemaker **102** has one or more structures that enable fixture to tissue, for example suture holes **224**, **225** or a helix **226**. The affixing structures enable implantation of the leadless pacemaker **102** directly to the cardiac muscle and with ligatures in procedures where the exterior surface of the heart can be accessed.

Also shown in FIG. 2, a cylindrical hermetic housing **110** is shown with annular electrodes **108** at housing extremities. In the illustrative embodiment, the housing **110** can be composed of alumina ceramic which provides insulation between the electrodes. The electrodes **108** are deposited on the ceramic, and are platinum or platinum-iridium.

Several techniques and structures can be used for attaching the housing **110** to the interior or exterior wall of cardiac chamber muscle **104**.

A helix **226** and slot **228** enable insertion of the device endocardially or epicardially through a guiding catheter. A screwdriver stylet can be used to rotate the housing **110** and force the helix **226** into muscle **104**, thus affixing the electrode **108A** in contact with stimutable tissue. Electrode **108B** serves as an indifferent electrode for sensing and pacing. The helix **226** may be coated for electrical insulation, and a steroid-eluting matrix may be included near the helix to minimize fibrotic reaction, as is known in conventional pacing electrode-leads.

In other configurations, suture holes **224** and **225** can be used to affix the device directly to cardiac muscle with ligatures, during procedures where the exterior surface of the heart is exposed.

Other attachment structures used with conventional cardiac electrode-leads including tines or barbs for grasping trabeculae in the interior of the ventricle, atrium, or coronary sinus may also be used in conjunction with or instead of the illustrative attachment structures.

Referring to FIG. 3, a pictorial view shows another embodiment of a single leadless cardiac pacemaker **102** that can be used in a cardiac pacing system **100** with at least one other pacemaker. The leadless cardiac pacemaker **102** includes a cylindrical metal housing **310** with an annular electrode **108A** and a second electrode **108B**. Housing **310** can be constructed from titanium or stainless steel. Electrode **108A** can be constructed using a platinum or platinum-iridium wire and a ceramic or glass feed-thru to provide electrical isolation from the metal housing. The housing can be coated with a biocompatible polymer such as medical grade silicone or polyurethane except for the region outlined by electrode **108B**. The distance between electrodes **108A** and **108B** should be approximately 1 cm to optimize sensing amplitudes and pacing thresholds. A helix **226** and slot **228** can be used for insertion of the device endocardially or epicardially through a guiding catheter. In addition, suture sleeves **302** and **303** made from silicone can be used to affix

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to the device directly to cardiac muscle with ligatures, for example in an epicardial or other application.

Referring to FIG. 4, a typical output-pulse waveform for a conventional pacemaker is shown. The approximately-exponential decay is due to discharge of a capacitor in the pacemaker through the approximately-resistive load presented by the electrodes and leads. Typically the generator output is capacitor-coupled to one electrode to ensure net charge balance. The pulse duration is shown as T0 and is typically 500 microseconds.

When the depicted leadless pacemaker 102 is used in combination with at least one other pacemaker or other pulse generator in the cardiac pacing system 100 and is generating a pacing pulse but is not optionally sending data for communication, the pacing waveform of the leadless pacemaker 102 can also resemble the conventional pacing pulse shown in FIG. 4.

Referring to FIG. 5, a time waveform graph depicts an embodiment of an output-pacing pulse waveform adapted for communication. The output-pulse waveform of the illustrative leadless pacemaker 102 is shown during a time when the pacemaker 102 is optionally sending data for communication and also delivering a pacing pulse, using the same pulse generator 116 and electrodes 108 for both functions.

FIG. 5 shows that the pulse generator 102 has divided the output pulse into shorter pulses 501, 502, 503, 504; separated by notches 505, 506, and 507. The pulse generator 102 times the notches 505, 506, and 507 to fall in timing windows W1, W2, and W4 designated 508, 509, and 511 respectively. Note that the pacemaker 102 does not form a notch in timing window W3 designated 510. The timing windows are each shown separated by a time T1, approximately 100 microseconds in the example.

As controlled by processor 112, pulse generator 116 selectively generates or does not generate a notch in each timing window 508, 509, 510, and 511 so that the device 102 encodes four bits of information in the pacing pulse. A similar scheme with more timing windows can send more or fewer bits per pacing pulse. The width of the notches is small, for example approximately 15 microseconds, so that the delivered charge and overall pulse width, specifically the sum of the widths of the shorter pulses, in the pacing pulse is substantially unchanged from that shown in FIG. 4. Accordingly, the pulse shown in FIG. 5 can have approximately the same pacing effectiveness as that shown in FIG. 4, according to the law of Lapique which is well known in the art of electrical stimulation.

In the leadless cardiac pacemaker 102, a technique can be used to conserve power when detecting information carried on pacing pulses from other implanted devices. The leadless cardiac pacemaker 102 can have multiple gain settings on the receiving or sensing amplifier 132, for example using a low-gain setting for normal operation. The low-gain setting could be insufficiently sensitive to decode gated information on a pacing pulse accurately, but could detect whether the pacing pulse is present. If an edge of a pacing pulse is detected during low-gain operation, the amplifier 132 can be switched quickly to the high-gain setting, enabling the detailed encoded data to be detected and decoded accurately. Once the pacing pulse has ended, the receiving amplifier 132 can be set back to low-gain. In the illustrative technique, a useful condition is that the receiving amplifier 132 shift to the more accurate high-gain quickly when called upon. To allow a maximum amount of time for shifting to occur, the encoded data can be placed at the end of the pacing pulse.

As an alternative or in addition to using notches in the stimulation pulse, the pulses can be generated with varying

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off-times, specifically times between pulses during which no stimulation occurs. The variation of off-times can be small, for example less than 10 milliseconds total, and can impart information based on the difference between a specific pulse's off-time and a preprogrammed off-time based on desired heart rate. For example, the device can impart four bits of information with each pulse by defining 16 off-times centered around the preprogrammed off-time. FIG. 6 is a graph showing a sample pulse generator output which incorporates a varying off-time scheme. In the figure, time T_p represents the preprogrammed pulse timing. Time T_d is the delta time associated with a single bit resolution for the data sent by the pulse generator. The number of T_d time increments before or after the moment specified by T_p gives the specific data element transmitted. The receiver of the pulse generator's communication has advance information of the time T_p . The communication scheme is primarily applicable to overdrive pacing in which time T_p is not dynamically changing or altered based on detected beats.

An aspect of proper functionality for a cardiac pacemaker is maintenance of a specified minimum internal supply voltage. When pacing tank capacitor charging occurs, the supply voltage can drop from a pre-charging level, a drop that can become more significant when the battery nears an end-of-life condition and has reduced current sourcing capability. Accordingly, in some implementations the leadless cardiac pacemaker 102 can be configured to stop charging the pacing tank capacitor when the supply voltage drops below a specified level. Accordingly, the processor 112 can be configured to control recharging of the tank capacitor so that recharging is discontinued when battery terminal voltage falls below a predetermined value, ensuring sufficient voltage for powering the leadless cardiac pacemaker circuitry. When charging ceases, the supply voltage returns to the value before charging began. In other implementations, the charge current can be lowered to prevent the supply voltage from dropping below the specified level, possibly creating difficulty in ensuring the same pacing rate or pacing pulse amplitude since the lower charge current results in the pacing tank taking longer to reach the desired voltage level.

FIG. 5 depicts a technique in which information is encoded in notches in the pacing pulse. FIG. 6 shows a technique of conveying information by modulating the off-time between pacing pulses. Alternatively or in addition to the two illustrative coding schemes, overall pacing pulse width can be used to impart information. For example, a paced atrial beat may exhibit a pulse width of 500 microseconds and an intrinsic atrial contraction can be identified by reducing the pulse width by 30 microseconds. Information can be encoded by the absolute pacing pulse width or relative shift in pulse width. Variations in pacing pulse width can be relatively small and have no impact on pacing effectiveness.

In some embodiments, a pacemaker 102 can use the leadless electrodes 108 to communicate bidirectionally among multiple leadless cardiac pacemakers and transmit data including designated codes for events detected or created by an individual pacemaker wherein the codes encode information using pacing pulse width.

The illustrative scheme for transmitting data does not significantly increase the current consumption of the pacemaker. For example, the pacemaker could transmit data continuously in a loop, with no consumption penalty.

The illustrative schemes for transmitting data enable assignment of designated codes to events detected or caused by a leadless cardiac pacemaker, such as sensing a heartbeat or delivering a pacing pulse at the location of the pacemaker that senses the event. Individual leadless cardiac pacemakers

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102 in a system **100** can be configured, either at manufacture or with an external programmer as described above, to issue a unique code corresponding to the type of event and location of the leadless cardiac pacemaker. By delivery of a coded pacing pulse with a code assigned according to the pacemaker location, a leadless cardiac pacemaker can transmit a message to any and all other leadless cardiac pacemakers implanted in the same patient, where the code signifies the origin of the event. Each other leadless cardiac pacemaker can react appropriately to the conveyed information in a predetermined manner encoded in the internal processor **112**, as a function of the type and location of the event coded in the received pulse. A leadless cardiac pacemaker **102** can thus communicate to any and all other co-implanted leadless cardiac pacemakers the occurrence of a sensed heartbeat at the originating pacemaker's location by generating a coded pacing pulse triggered by the sensed event. Triggered pacing occurs in the natural refractory period following the heartbeat and therefore has no effect on the chamber where the leadless cardiac pacemaker is located.

Referring again to FIG. 1B, the circuit **132** for receiving communication via electrodes **108** receives the triggering information as described and can also optionally receive other communication information, either from the other implanted pulse generator **106** or from a programmer outside the body. This other communication could be coded with a pulse-position scheme as described in FIG. 5 or could otherwise be a pulse-modulated or frequency-modulated carrier signal, preferably from 10 kHz to 100 kHz. The illustrative scheme of a modulated carrier is applicable not only to intercommunication among multiple implanted pacemakers but also is applicable to communication from an external programmer.

The illustrative leadless pacemaker **102** could otherwise receive triggering information from the other pulse generator **106** implanted within the body via a pulse-modulated or frequency-modulated carrier signal, instead of via the pacing pulses of the other pulse generator **106**.

With regard to operating power requirements in the leadless cardiac pacemaker **102**, for purposes of analysis, a pacing pulse of 5 volts and 5 milliamps amplitude with duration of 500 microseconds and a period of 500 milliseconds has a power requirement of 25 microwatts.

In an example embodiment of the leadless pacemaker **102**, the processor **112** typically includes a timer with a slow clock that times a period of approximately 10 milliseconds and an instruction-execution clock that times a period of approximately 1 microsecond. The processor **112** typically operates the instruction-execution clock only briefly in response to events originating with the timer, communication amplifier **134**, or cardiac sensing amplifier **132**. At other times, only the slow clock and timer operate so that the power requirement of the processor **112** is no more than 5 microwatts.

For a pacemaker that operates with the aforementioned slow clock, the instantaneous power consumption specification, even for a commercially-available micropower microprocessor, would exceed the battery's power capabilities and would require an additional filter capacitor across the battery to prevent a drop of battery voltage below the voltage necessary to operate the circuit. The filter capacitor would add avoidable cost, volume, and potentially lower reliability.

For example, a microprocessor consuming only 100 microamps would require a filter capacitor of 5 microfarads to maintain a voltage drop of less than 0.1 volt, even if the processor operates for only 5 milliseconds. To avoid the necessity for such a filter capacitor, an illustrative embodiment of a processor can operate from a lower frequency clock to avoid the high instantaneous power consumption, or the

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processor can be implemented using dedicated hardware state machines to supply a lower instantaneous peak power specification.

In a pacemaker, the cardiac sensing amplifier typically operates with no more than 5 microwatts. A communication amplifier at 100 kHz operates with no more than 25 microwatts. The battery ammeter and battery voltmeter operate with no more than 1 microwatt each.

A pulse generator typically includes an independent rate limiter with a power consumption of no more than 2 microwatts.

The total power consumption of the pacemaker is thus 64 microwatts, less than the disclosed 70-microwatt battery output.

Improvement attained by the illustrative cardiac pacing system **100** and leadless cardiac pacemaker **102** is apparent.

In a specific embodiment, the outgoing communication power requirement plus the pacing power requirement does not exceed approximately 25 microwatts. In other words, outgoing communication adds essentially no power to the power used for pacing.

The illustrative leadless cardiac pacemaker **102** can have sensing and processing circuitry that consumes no more than 10 microwatts as in conventional pacemakers.

The described leadless cardiac pacemaker **102** can have an incoming communication amplifier for receiving triggering signals and optionally other communication which consumes no more than 25 microwatts.

Furthermore, the leadless cardiac pacemaker **102** can have a primary battery that exhibits an energy density of at least 3 watt-hours per cubic centimeter (W·h/cc).

In an illustrative application of the cardiac pacing system **100**, multiple leadless cardiac pacemakers **102** can be co-implanted in a single patient to provide a system for dual-chamber pacing, CRT-P, or any other multi-chamber pacing application. Each leadless cardiac pacemaker in the system can use the illustrative communication structures to communicate the occurrence of a sensed heartbeat or a delivered pacing pulse at the location of sensing or delivery, and a communication code can be assigned to each combination of event type and location. Each leadless cardiac pacemaker can receive the transmitted information, and the code of the information can signify that a paced or sensed event has occurred at another location and indicate the location of occurrence. The receiving leadless cardiac pacemaker's processor **112** can decode the information and respond appropriately, depending on the location of the receiving pacemaker and the desired function of the system. FIGS. 7 and 8 are state diagrams that illustrate application of illustrative combined control operations in an atrial and right-ventricular leadless cardiac pacemaker respectively, to implement a simple dual-chamber pacing system when co-implanted. FIG. 9 is a state diagram that illustrates inclusion of a left-ventricular leadless cardiac pacemaker to form a CRT-P system.

In various embodiments, each leadless cardiac pacemaker may also encode other information destined for co-implanted leadless cardiac pacemakers, besides markers of paced or sensed events.

For clarity of illustration, descriptions of the atrial, right ventricular, and left-ventricular leadless cardiac pacemakers in respective FIGS. 7, 8, and 9 show only basic functions of each pacemaker. Other functions such as refractory periods, fallback mode switching, algorithms to prevent pacemaker-mediated tachycardia, and the like, can be added to the leadless cardiac pacemakers and to the system in combination.

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Also for clarity, functions for communication with an external programmer are not shown and are shown elsewhere herein.

Referring to FIG. 7, a state-mechanical representation shows operation of a leadless cardiac pacemaker for implan-

tation adjacent to atrial cardiac muscle. As explained above, a leadless cardiac pacemaker can be configured for operation in a particular location and system either at manufacture or by an external programmer. Similarly, all individual pacemakers of the multiple pacemaker system can be configured for operation in a particular location and a particular functionality at manufacture and/or at programming by an external programmer wherein “configuring” means defining logic such as a state machine and pulse codes used by the leadless cardiac pacemaker.

In a cardiac pacing system, the multiple leadless cardiac pacemakers can comprise an atrial leadless cardiac pacemaker implanted in electrical contact to an atrial cardiac chamber. The atrial leadless cardiac pacemaker can be configured or programmed to perform several control operations **700** in combination with one or more other pacemakers. In a wait state **702** the atrial leadless cardiac pacemaker waits for an earliest occurring event of multiple events including a sensed atrial heartbeat **704**, a communication of an event sensed on the at least two leadless electrodes encoding a pacing pulse marking a heartbeat **706** at a ventricular leadless cardiac pacemaker, or timeout of an interval timed locally in the atrial leadless cardiac pacemaker shown as escape interval timeout **708**. The atrial pacemaker responds to a sensed atrial heartbeat **704** by generating **710** an atrial pacing pulse that signals to one or more other pacemakers that an atrial heartbeat has occurred, encoding the atrial pacing pulse with a code signifying an atrial location and a sensed event type. The atrial pacing pulse can be encoded using the technique shown in FIG. 5 with a unique code signifying the location in the atrium. After pacing the atrium, the atrial cardiac pacemaker times **712** a predetermined atrial-to-atrial (AA) escape interval. Accordingly, the atrial leadless cardiac pacemaker restarts timing **712** for a predetermined escape interval, called the AA (atrial to atrial) escape interval, which is the time until the next atrial pacing pulse if no other event intervenes. The atrial leadless cardiac pacemaker then re-enters the Wait state **702**. The atrial pacemaker also responds to timeout of a first occurring escape interval **708** by delivering an atrial pacing pulse **710**, causing an atrial heartbeat with the atrial pacing pulse encoding paced type and atrial location of an atrial heartbeat event. When the atrial escape interval times out, shown as transition **708**, the atrial leadless cardiac pacemaker delivers an atrial pacing pulse. Because no other atrial heartbeat has occurred during the duration of the escape interval, the atrial pacing pulse does not fall in the atria’s natural refractory period and therefore should effectively pace the atrium, causing an atrial heartbeat. The atrial pacing pulse, coded in the manner shown in FIG. 5, also signals to any and all other co-implanted leadless cardiac pacemakers that an atrial heartbeat has occurred. If functionality is enhanced for a more complex system, the atrial leadless cardiac pacemaker can use a different code to signify synchronous pacing triggered by an atrial sensed event in comparison to the code used to signify atrial pacing at the end of an escape interval. However, in the simple example shown in FIGS. 7 and 8, the same code can be used for all atrial pacing pulses. In fact, for the simple dual-chamber pacing system described in FIGS. 7 and 8 encoding may be omitted because each leadless cardiac pacemaker can conclude that any detected pacing pulse, which is not generated locally, must have originated with the other co-implanted leadless cardiac pacemaker. After gener-

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ating the atrial pacing pulse **710**, the atrial leadless cardiac pacemaker starts timing an atrial (AA) escape interval at action **712**, and then returns to the wait state **702**.

The atrial leadless cardiac pacemaker can further operate in response to another pacemaker. The atrial pacemaker can detect **706** a signal originating from a co-implanted ventricular leadless cardiac pacemaker. The atrial pacemaker can examine the elapsed amount of the atrial-to-atrial (AA) escape time interval since a most recent atrial heartbeat and determine **714** whether the signal originating from the co-implanted ventricular leadless cardiac pacemaker is premature. Thus, if the atrial leadless cardiac pacemaker detects a signal originating from a co-implanted ventricular leadless cardiac pacemaker, shown as sensed ventricular pacing **706**, then the atrial device examines the amount of the escape interval elapsed since the last atrial heartbeat at decision point **714** to determine whether the ventricular event is “premature”, meaning too late to be physiologically associated with the last atrial heartbeat and in effect premature with respect to the next atrial heartbeat. In the absence **716** of a premature signal, the atrial pacemaker waits **702** for an event with no effect on atrial pacing. In contrast if the signal is premature **718**, the pacemaker restarts **720** a ventricle-to-atrium (VA) escape interval that is shorter than the atrial-to-atrial (AA) escape interval and is representative of a typical time from a ventricular beat to a next atrial beat in sinus rhythm, specifically the atrial interval minus the atrio-ventricular conduction time. After starting **720** the VA interval, the atrial leadless cardiac pacemaker returns to wait state **702**, whereby a ventricular premature beat can be said to “recycle” the atrial pacemaker. The pacemaker responds to timeout of the atrial-to-atrial (AA) escape interval **708** by delivering an atrial pacing pulse **710**, causing an atrial heartbeat. The atrial pacing pulse encodes the paced type and atrial location of an atrial heartbeat event.

The atrial leadless cardiac pacemaker can be further configured to time a prolonged post-ventricular atrial refractory period (PVARP) after recycling in presence of the premature signal, thereby preventing pacemaker-mediated tachycardia (PMT). Otherwise, if a received ventricular pacing signal evaluated at decision point **714** is not found to be premature, then the atrial leadless cardiac pacemaker follows transition **716** and re-enters the wait state **702** without recycling, thus without any effect on the timing of the next atrial pacing pulse.

Referring to FIG. 8, a state-mechanical representation depicts operation of a leadless cardiac pacemaker for implantation adjacent to right-ventricular cardiac muscle. The leadless cardiac pacemaker can be configured for operation in a particular location and system either at manufacture or by an external programmer. A system comprising multiple leadless cardiac pacemakers can include a right-ventricular leadless cardiac pacemaker implanted in electrical contact to a right-ventricular cardiac chamber. The right-ventricular leadless cardiac pacemaker can be configured to perform actions **800** for coordinated pacing in combination with the other pacemakers. The right-ventricular leadless cardiac pacemaker waits **802** for the earliest occurring event of multiple events including a sensed right-ventricular heartbeat **804**, a sensed communication of a pacing pulse **806** marking a heartbeat at an atrial leadless cardiac pacemaker, and timeout **808** of an escape interval. Generally, the sensed communication of a pacing pulse **806** can be any suitable sensed communication of an event originating at another co-implanted leadless cardiac pacemaker, in the illustrative embodiment a pacing pulse marking a heartbeat at an atrial leadless cardiac pacemaker shown as sensed atrial pacing. The escape interval timeout

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808 can be any suitable timeout of an interval timed locally in the right-ventricular leadless cardiac pacemaker.

The right-ventricular leadless cardiac pacemaker responds to the sensed right-ventricular heartbeat **804** by generating **810** a right-ventricular pacing pulse that signals to at least one other pacemaker of the multiple cardiac pacemakers that a right-ventricular heartbeat has occurred. Thus, when a sensed right-ventricular heartbeat occurs **804**, the right-ventricular leadless cardiac pacemaker generates **810** a right-ventricular pacing pulse, not to pace the heart but rather to signal to another leadless cardiac pacemaker or pacemakers that a right-ventricular heartbeat has occurred. The right-ventricular pacing pulse can be encoded with a code signifying the right-ventricular location and a sensed event type. The right-ventricular pacing pulse is coded in the manner shown in FIG. 5 with a unique code signifying the location in the right ventricle. Upon right-ventricular pacing pulse generation **810**, the right-ventricular leadless cardiac pacemaker can time **812** a predetermined right ventricular-to-right ventricular (VV) escape interval. The right-ventricular leadless cardiac pacemaker restarts **812** timing of a predetermined escape interval, called the VV (right-ventricular to right-ventricular) escape interval, which is the time until the next right-ventricular pacing pulse if no other event intervenes. The VV escape interval is started after delivering a ventricular pacing pulse subsequent to various events including an atrial-ventricular (AV) delay, a ventricular-to-ventricular (VV) delay, or a ventricular sensed event.

The right-ventricular leadless cardiac pacemaker can further be configured to set the ventricular-to-ventricular (VV) escape interval longer than a predetermined atrial-to-atrial (AA) escape interval to enable backup ventricular pacing at a low rate corresponding to the VV escape interval in case of failure of a triggered signal from a co-implanted atrial leadless cardiac pacemaker. Typically, the VV (right) escape interval is longer than the AA interval depicted in FIG. 7, so that the system supports backup ventricular pacing at a relatively low rate in case of failure of the co-implanted atrial leadless cardiac pacemaker. In normal operation of the system, timeout of the VV interval never occurs. The right-ventricular leadless cardiac pacemaker then re-enters the Wait state **802**.

The right-ventricular leadless cardiac pacemaker can respond to timeout of a first occurring escape interval **808** by delivering **810** a right ventricular pacing pulse, causing a right ventricular heartbeat. The right ventricular pacing pulse can encode information including paced type and right-ventricular location of a right ventricular heartbeat event.

When the right-ventricular escape interval times out **808**, the right-ventricular leadless cardiac pacemaker delivers **810** a right-ventricular pacing pulse. Because no other right-ventricular heartbeat has occurred during the duration of the VV escape interval, the pacing pulse **810** does not fall in the ventricles' natural refractory period and therefore should effectively pace the ventricles, causing a ventricular heartbeat. The right-ventricular pacing pulse, coded in the manner shown in FIG. 5, also signals to any and all other co-implanted leadless cardiac pacemakers that a right-ventricular heartbeat has occurred. If useful for the function of a more complex system, the right-ventricular leadless cardiac pacemaker can use a different code to signify synchronous pacing triggered by a right-ventricular sensed event in comparison to the code used to signify right-ventricular pacing at the end of a VV escape interval. However, in the simple example shown in FIGS. 7 and 8, the same code can be used for all right-ventricular pacing pulses. In fact, for the simple dual-chamber pacing system described in FIGS. 7 and 8, a code may be omitted because each leadless cardiac pacemaker can con-

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clude that any detected pacing pulse which is not generated local to the pacemaker originates with the other co-implanted leadless cardiac pacemaker. After generating **810** the right-ventricular pacing pulse, the right-ventricular leadless cardiac pacemaker starts timing **812** a right-ventricular escape interval VV, and then returns to the wait state **802**.

The right-ventricular leadless cardiac pacemaker can further be configured to detect **806** a signal originating from a co-implanted atrial leadless cardiac pacemaker. The right-ventricular leadless cardiac pacemaker examines the elapsed amount of the ventricular-to-ventricular (VV) escape interval since a most recent right-ventricular heartbeat and determines **814** whether the signal originating from the co-implanted atrial leadless cardiac pacemaker is premature. An atrial event is defined as premature if too early to trigger an atrio-ventricular delay to produce a right-ventricular heartbeat. In the presence of a premature signal **816**, the right-ventricular leadless cardiac pacemaker returns to the wait state **802** with no further action. Thus, a premature atrial beat does not affect ventricular pacing. In the absence of a premature signal **818**, the right-ventricular leadless cardiac pacemaker starts **820** a right atrium to right ventricular (AV) escape interval that is representative of a typical time from an atrial beat to a right-ventricular beat in sinus rhythm. Thus a non-premature atrial event leads to starting **820** an AV (right) atrium to right-ventricular escape interval that represents a typical time from an atrial beat to a right-ventricular beat in normally-conducted sinus rhythm. After starting **820** the AV interval, the right-ventricular leadless cardiac pacemaker returns to the wait state **802** so that a non-premature atrial beat can "trigger" the right-ventricular pacemaker after a physiological delay. The right-ventricular leadless cardiac pacemaker also responds to timeout of either the VV escape interval and the AV escape interval **808** by delivering **810** a right ventricular pacing pulse, causing a right ventricular heartbeat. The right ventricular pacing pulse encodes paced type and right-ventricular location of a right ventricular heartbeat event.

Accordingly, co-implanted atrial and right-ventricular leadless cardiac pacemakers depicted in FIGS. 7 and 8 cooperate to form a dual-chamber pacing system.

Referring to FIG. 9, a state-mechanical representation illustrates the operation of a leadless cardiac pacemaker for implantation adjacent to left-ventricular cardiac muscle. The left-ventricular cardiac pacemaker can be used in combination with the dual-chamber pacemaker that includes atrial leadless cardiac pacemaker and the right-ventricular leadless cardiac pacemaker described in FIGS. 7 and 8 respectively to form a system for CRT-P. A leadless cardiac pacemaker, for example the left-ventricular cardiac pacemaker, can be configured for operation in a particular location and system either at manufacture or by an external programmer.

A cardiac pacing system, such as a CRT-P system, can include multiple leadless cardiac pacemakers including a left-ventricular leadless cardiac pacemaker implanted in electrical contact to a left-ventricular cardiac chamber. The left-ventricular leadless cardiac pacemaker can execute operations of an illustrative pacing method **900**. In a wait state **902**, the left-ventricular cardiac pacemaker waits **902** at the left-ventricular leadless cardiac pacemaker for an earliest occurring event of multiple events including a sensed communication **904** of a pacing pulse marking a heartbeat at an atrial leadless cardiac pacemaker and timeout **906** of a left ventricular escape interval. Generally, the sensed communication **904** can be the sensed communication of an event originating at another co-implanted leadless cardiac pacemaker, in the illustrative embodiment a pacing pulse marking a heartbeat at an atrial leadless cardiac pacemaker shown as

sensed atrial pacing. The escape interval timeout **906** can be timeout of an interval timed locally in the left-ventricular leadless cardiac pacemaker. In the wait state **902** for the left-ventricular leadless cardiac pacemaker, operation is simplified and the left-ventricular pacemaker does not respond to left-ventricular heartbeats. Also, the left-ventricular cardiac pacemaker does not pace the left ventricle in the absence of a triggering signal from the atrial leadless cardiac pacemaker. The left-ventricular cardiac pacemaker responds to timeout **906** of the left ventricular escape interval by delivering **908** a left ventricular pacing pulse, causing a left ventricular heartbeat. The left ventricular pacing pulse encodes the type and location of a left ventricular heartbeat event. The left-ventricular pacing pulse can be coded in the manner shown in FIG. 5 to communicate signals to any and all other co-implanted leadless cardiac pacemakers that a left-ventricular heartbeat has occurred, although such encoding is not necessary in the simplified CRT-P system shown in the described embodiment because the other leadless cardiac pacemakers do not react to left-ventricular pacing. After generating **908** the left-ventricular pacing pulse, the left-ventricular leadless cardiac pacemaker returns to the wait state **902**.

The left-ventricular leadless cardiac pacemaker can be further configured detect a signal originating from a co-implanted atrial leadless cardiac pacemaker and examine the elapsed amount of the left ventricular escape interval since a most recent left-ventricular heartbeat. The left-ventricular cardiac pacemaker can determine **910** whether the signal originating from the co-implanted atrial leadless cardiac pacemaker is premature. If the left-ventricular leadless cardiac pacemaker detects sensed atrial pacing, then the left-ventricular device determines whether the atrial event is premature, meaning too early to trigger an atrio-ventricular delay to produce a left-ventricular heartbeat. In the presence of a premature signal **912**, the left-ventricular cardiac pacemaker reverts to the wait state **902** and waits for an event with no effect on ventricular pacing so that a premature atrial beat does not affect ventricular pacing. In absence of a premature signal **914**, the left-ventricular cardiac pacemaker starts **916** a left atrium to left ventricular (AV) escape interval that is representative of a typical time from an atrial beat to a left ventricular beat in normally-conducted sinus rhythm. As shown in the depicted embodiment, the AV (left) escape interval can have a different value from the AV (right) escape interval. After starting **916** the AV interval, the left-ventricular leadless cardiac pacemaker returns to wait state **902**. Accordingly, a non-premature atrial beat can “trigger” the left-ventricular pacemaker after a physiological delay.

The left-ventricular cardiac pacemaker also responds to timeout **906** of the AV escape interval by delivering **908** a left ventricular pacing pulse, causing a left ventricular heartbeat. The left ventricular pacing pulse encodes paced type and left ventricular location of a left ventricular heartbeat event.

In various embodiments, the multiple leadless cardiac pacemakers can comprise a right ventricular leadless cardiac pacemaker and a left ventricular leadless cardiac pacemaker that are configured to operate with atrio-ventricular (AV) delays whereby a left ventricular pacing pulse can be delivered before, after, or substantially simultaneously with a right ventricular pacing pulse. For example, multiple co-implanted leadless cardiac pacemakers that function according to the state diagrams shown in FIGS. 7, 8, and 9 can support CRT-P with left-ventricular pacing delivered before, at the same time as, or after right-ventricular pacing.

In various embodiments, multiple co-implanted leadless cardiac pacemakers can be configured for multi-site pacing that synchronizes depolarization for tachyarrhythmia prevention.

Referring to FIGS. 10A and 10B, schematic flow charts illustrate an embodiment of a method for operating an atrial leadless cardiac pacemaker in multi-chamber cardiac pacing. FIG. 10A depicts a method **1000** for multi-chamber cardiac pacing comprising configuring **1002** a multiple leadless cardiac pacemakers for implantation and configuring **1004** an atrial leadless cardiac pacemaker of the multiple leadless cardiac pacemakers for implantation in electrical contact to an atrial cardiac chamber. The atrial leadless cardiac pacemaker waits **1006** for an earliest occurring event of multiple events including a sensed atrial heartbeat, a communication of an event sensed on the at least two leadless electrodes encoding a pacing pulse marking a heartbeat at a ventricular leadless cardiac pacemaker, and timeout of an atrial-to-atrial (AA) escape interval. The atrial leadless cardiac pacemaker responds **1008** to the sensed atrial heartbeat by generating an atrial pacing pulse that signals to at least one pacemaker of the multiple leadless cardiac pacemakers that an atrial heartbeat has occurred and that encodes the atrial pacing pulse with a code signifying an atrial location and a sensed event type. After either a sensed atrial heartbeat or timeout of an escape interval, the atrial leadless cardiac pacemaker delivers **1010** an atrial pacing pulse, causing an atrial heartbeat and starts **1012** timing a predetermined length AA escape interval, then waiting **1006** for an event. The atrial pacing pulse identifies paced type and/or atrial location of an atrial heartbeat event.

In some embodiments, the atrial leadless cardiac pacemaker can encode an atrial pacing pulse that identifies synchronous pacing triggered by an atrial sensed event with a first code and encode an atrial pacing pulse that identifies atrial pacing following the AA escape interval with a second code distinct from the first code.

In some embodiments or conditions, the atrial leadless cardiac pacemaker can deliver the atrial pacing pulse in absence of encoding whereby, for dual-chamber cardiac pacing, a pacing pulse that is not generated in a first cardiac pacemaker that senses the pacing pulse is necessarily generated in a second cardiac pacemaker. Accordingly, neither the use of a code to identify the chamber corresponding to a pacing pulse, nor the use of a code to identify the type of pulse (whether paced or sensed) is a necessary step in a simple system such as a dual chamber pacing system disclosed in the specification.

The atrial leadless cardiac pacemaker can, upon delivery of an atrial pacing pulse, time an atrial-to-atrial (AA) escape interval.

FIG. 10B is a flow chart showing another aspect of an embodiment of a method **1050** for operating an atrial leadless cardiac pacemaker. The atrial leadless cardiac pacemaker detects **1052** a signal originating from a co-implanted ventricular leadless cardiac pacemaker and examines **1054** an elapsed amount of the atrial-to-atrial (AA) escape interval since a most recent atrial heartbeat, determining **1056** whether the signal originating from the co-implanted ventricular leadless cardiac pacemaker is premature. In absence of a premature signal **1058**, the atrial leadless cardiac pacemaker waits **1060** for an event with no effect on atrial pacing, returning to wait state **1006**. In presence of a premature signal **1062**, the atrial leadless cardiac pacemaker restarts **1064** a ventricle-to-atrium (VA) escape interval that is shorter than the atrial-to-atrial (AA) escape interval and representative of a typical time from a ventricular beat to a next atrial beat in sinus rhythm, then returns to wait state **1006**.

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Referring to FIGS. 11A and 11B, schematic flow charts illustrate an embodiment of a method for operating a right-ventricular leadless cardiac pacemaker in multi-chamber cardiac pacing. FIG. 11A depicts a method 1100 for multi-chamber cardiac pacing comprising configuring 1102 a plurality of leadless cardiac pacemakers for implantation and configuring 1104 a right-ventricular leadless cardiac pacemaker of the multiple leadless cardiac pacemakers for implantation in electrical contact to a right-ventricular cardiac chamber. The right-ventricular leadless cardiac pacemaker waits 1106 for an earliest occurring event of a several events including a sensed right-ventricular heartbeat, a sensed communication of a pacing pulse marking a heartbeat at an atrial leadless cardiac pacemaker, and timeout of an escape interval. The right-ventricular leadless cardiac pacemaker responds 1108 to the sensed right-ventricular heartbeat by generating a right-ventricular pacing pulse that signals to at least one pacemaker of the leadless cardiac pacemakers that a right-ventricular heartbeat has occurred and that encodes the right-ventricular pacing pulse with a code signifying a right-ventricular location and a sensed event type. The right-ventricular leadless cardiac pacemaker responds 1110 to timeout of a first occurring escape interval by delivering a right ventricular pacing pulse, causing a right ventricular heartbeat, with the right ventricular pacing pulse encoding paced type and right ventricular location of a right ventricular heartbeat event, and times 1112 a predetermined ventricular-to-ventricular (VV) escape interval.

In some embodiments, the right-ventricular leadless cardiac pacemaker can encode a right-ventricular pacing pulse that identifies synchronous pacing triggered by a right-ventricular sensed event with a first code and encode a right-ventricular pacing pulse that identifies right-ventricular pacing following a ventricular-to-ventricular (VV) escape interval with a second code distinct from the first code.

In some embodiments, the right-ventricular leadless cardiac pacemaker, upon delivery of a right-ventricular pacing pulse, can time a ventricular-to-ventricular (VV) escape interval.

FIG. 11B is a flow chart showing another aspect of an embodiment of a method 1150 for operating a right-ventricular leadless cardiac pacemaker. The right-ventricular leadless cardiac pacemaker detects 1152 a signal originating from a co-implanted atrial leadless cardiac pacemaker, examines 1154 the elapsed amount of the ventricular-to-ventricular (VV) escape interval since a most recent right-ventricular heartbeat, and determines 1156 whether the signal originating from the co-implanted atrial leadless cardiac pacemaker is premature. In presence 1158 of a premature signal, the right-ventricular leadless cardiac pacemaker waits 1160 for an event with no effect on ventricular pacing, returning to wait state 1106. In absence 1162 of a premature signal, the right-ventricular leadless cardiac pacemaker starts 1164 a right atrium to right ventricular (AV) escape interval that is representative of a typical time from an atrial beat to a right-ventricular beat in sinus rhythm, and then returns to the wait state 1106.

Referring to FIGS. 12A and 12B, schematic flow charts illustrate embodiments of a method for operating a left-ventricular leadless cardiac pacemaker in multi-chamber cardiac pacing. FIG. 12A depicts a method 1200 for multi-chamber cardiac pacing comprising configuring 1202 a plurality of leadless cardiac pacemakers for implantation and configuring 1204 a left-ventricular leadless cardiac pacemaker of the leadless cardiac pacemaker plurality for implantation in electrical contact to a left-ventricular cardiac chamber and for operation in cardiac resynchronization therapy (CRT-P). The

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left-ventricular cardiac pacemaker waits 1206 at the left-ventricular leadless cardiac pacemaker for an earliest occurring event of a plurality of events comprising a sensed communication of a pacing pulse marking a heartbeat at an atrial leadless cardiac pacemaker and timeout of a left ventricular escape interval. The left-ventricular cardiac pacemaker responds 1208 to timeout of the left ventricular escape interval by delivering a left ventricular pacing pulse, causing a left ventricular heartbeat, the left ventricular pacing pulse encoding type and location of a left ventricular heartbeat event.

In some embodiments, the left-ventricular cardiac pacemaker can configure the left-ventricular leadless cardiac pacemaker for operation in cardiac resynchronization therapy (CRT-P).

FIG. 12B is a flow chart showing another aspect of an embodiment of a method 1250 for operating a left-ventricular leadless cardiac pacemaker. The left-ventricular leadless cardiac pacemaker detects 1252 a signal originating from a co-implanted atrial leadless cardiac pacemaker, examines 1254 the elapsed amount of the left ventricular escape interval since a most recent left-ventricular heartbeat, and determines 1256 whether the signal originating from the co-implanted atrial leadless cardiac pacemaker is premature. In the presence 1258 of a premature signal, the left-ventricular cardiac pacemaker waits 1260 for an event with no effect on ventricular pacing. In the absence 1262 of a premature signal, the left-ventricular cardiac pacemaker starts 1264 a left atrium to left ventricular (AV) escape interval that is representative of a typical time from an atrial beat to a left ventricular beat in sinus rhythm.

Terms “substantially”, “essentially”, or “approximately”, that may be used herein, relate to an industry-accepted tolerance to the corresponding term. Such an industry-accepted tolerance ranges from less than one percent to twenty percent and corresponds to, but is not limited to, component values, integrated circuit process variations, temperature variations, rise and fall times, and/or thermal noise. The term “coupled”, as may be used herein, includes direct coupling and indirect coupling via another component, element, circuit, or module where, for indirect coupling, the intervening component, element, circuit, or module does not modify the information of a signal but may adjust its current level, voltage level, and/or power level. Inferred coupling, for example where one element is coupled to another element by inference, includes direct and indirect coupling between two elements in the same manner as “coupled”.

While the present disclosure describes various embodiments, these embodiments are to be understood as illustrative and do not limit the claim scope. Many variations, modifications, additions and improvements of the described embodiments are possible. For example, those having ordinary skill in the art will readily implement the steps necessary to provide the structures and methods disclosed herein, and will understand that the process parameters, materials, and dimensions are given by way of example only. The parameters, materials, and dimensions can be varied to achieve the desired structure as well as modifications, which are within the scope of the claims. Variations and modifications of the embodiments disclosed herein may also be made while remaining within the scope of the following claims. For example, although the description has some focus on the pacemaker, system, structures, and techniques can otherwise be applicable to other uses, for example multi-site pacing for prevention of tachycardias in the atria or ventricles. Phraseology and terminology employed herein are for the purpose of the description and should not be regarded as limiting. With respect to the description, optimum dimensional relation-

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ships for the component parts are to include variations in size, materials, shape, form, function and manner of operation, assembly and use that are deemed readily apparent and obvious to one of ordinary skill in the art and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present description. Therefore, the foregoing is considered as illustrative only of the principles of structure and operation. Numerous modifications and changes will readily occur to those of ordinary skill in the art whereby the scope is not limited to the exact construction and operation shown and described, and accordingly, all suitable modifications and equivalents may be included.

What is claimed is:

1. A cardiac pacing system comprising:

a plurality of leadless cardiac pacemakers individually configured for implantation in electrical contact with a cardiac chamber and configured in combination for multi-chamber cardiac pacing, the leadless cardiac pacemaker plurality individually comprising at least two leadless pacing electrodes and a controller operatively connected to the electrodes and configured to deliver cardiac pacing pulses through the electrodes, sense evoked and/or natural cardiac electrical signals through the electrodes, and bidirectionally communicate information through the electrodes for coordinating pacing among the plurality of leadless cardiac pacemakers.

2. The system according to claim 1 wherein:

the controller of at least one pacemaker of the plurality of leadless cardiac pacemakers is further configured to communicate with a non-implanted programmer via the at least two pacing electrodes using antenna-less and telemetry coil-less communication.

3. A system according to claim 1 wherein:

individual pacemakers of the plurality of leadless cardiac pacemakers comprise:

a hermetic housing configured for placement on or attachment to the inside or outside of a cardiac chamber; and

the at least two leadless pacing electrodes proximal to the housing configured for bidirectional communication with at least one other device within or outside the body.

4. The system according to claim 1 wherein:

the at least two leadless pacing electrodes are configured to communicate bidirectionally among the plurality of leadless cardiac pacemakers to coordinate pacing pulse delivery using messages that identify an event at an individual pacemaker originating the message and pacemakers receiving the message react as directed by the message depending on the message origin.

5. The system according to claim 1 wherein:

the at least two leadless pacing electrodes are configured to communicate bidirectionally among the plurality of leadless cardiac pacemakers and transmit data including designated codes for events detected or created by an individual pacemaker, the individual pacemakers configured to issue a unique code that identifies an event type and a location of the individual pacemaker.

6. The system according to claim 1 wherein:

individual pacemakers of the plurality of leadless cardiac pacemakers are configured to deliver at least one pulse encoded with a code assigned according to pacemaker location and configured to transmit a message to at least one pacemaker of the plurality of leadless cardiac pacemakers via the encoded at least one pulse wherein the code identifies the individual pacemaker originating an

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event, the at least one pacemaker receiving the message being adapted to respond to the message in a predetermined manner depending on type and location of the event.

7. The system according to claim 1 wherein:

individual pacemakers of the plurality of leadless cardiac pacemakers are configured to communicate to at least one pacemaker of the plurality of leadless cardiac pacemakers occurrence of a sensed heartbeat at the individual pacemaker location via generation of at least one coded pulse triggered by a sensed heartbeat in a natural refractory period following the sensed heartbeat.

8. The system according to claim 1 wherein:

the plurality of leadless cardiac pacemakers is configured for co-implantation in a single patient and multiple-chamber pacing, the bidirectional communication among the plurality of leadless cardiac pacemakers adapted to communicate notification of a sensed heartbeat or delivered pacing pulse event to at least one pacemaker of the plurality of leadless cardiac pacemakers, the at least one pacemaker that receives the communication adapted to decode the information and respond depending on location of the receiving pacemaker and predetermined system functionality.

9. The system according to claim 1 wherein:

the plurality of leadless cardiac pacemakers comprises an atrial leadless cardiac pacemaker adapted for implantation in electrical contact to an atrial cardiac chamber, the atrial leadless cardiac pacemaker configured to:

wait for an earliest occurring event of a plurality of events comprising a sensed atrial heartbeat, a communication of an event sensed on the at least two leadless pacing electrodes encoding at least one pulse generated by a ventricular pulse generator and marking a heartbeat at a ventricular leadless cardiac pacemaker, or timeout of an escape interval;

respond to the sensed atrial heartbeat by generating at least one pulse via an atrial pulse generator that signals to at least one pacemaker of the plurality of leadless cardiac pacemakers that an atrial heartbeat has occurred and encoding at least one pulse generated by an atrial pulse generator with a code signifying an atrial location and a sensed event type; time a predetermined atrial-to-atrial (AA) escape interval; and

respond to timeout of an escape interval by delivering an atrial pacing pulse, causing an atrial heartbeat, and encoding at least one pulse generated by the atrial pulse generator with information designating paced type and atrial location of an atrial heartbeat event.

10. The system according to claim 9 wherein:

the atrial leadless cardiac pacemaker is configured to time an atrial-to-atrial (AA) escape interval after generating an atrial pacing pulse.

11. The system according to claim 9 wherein:

the atrial leadless cardiac pacemaker is configured to: detect a signal originating from a co-implanted ventricular leadless cardiac pacemaker; examine an elapsed amount of the atrial-to-atrial (AA) escape interval since a most recent atrial heartbeat; determine whether the signal originating from the co-implanted ventricular leadless cardiac pacemaker is premature; in absence of a premature signal, wait for an event with no effect on atrial pacing; in presence of a premature signal, restart a ventricle-to-atrial (VA) escape interval that is shorter than the

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atrial-to-atrial (AA) escape interval and representative of a typical time from a ventricular beat to a next atrial beat in sinus rhythm; and
 respond to timeout of the VA escape interval or the AA escape interval by delivering an atrial pacing pulse, causing an atrial heartbeat, encoding at least one pulse generated by the atrial pulse generator with information designating paced type and atrial location of an atrial heartbeat event, and starting an AA escape interval and returning to a wait state.

12. The system according to claim 11 wherein:
 the atrial leadless cardiac pacemaker is further configured to:
 time a prolonged post-ventricular atrial refractory period (PVARP) after recycling in presence of the premature signal whereby pacemaker-mediated tachycardia is prevented.

13. The system according to claim 1 wherein:
 the plurality of leadless cardiac pacemakers comprise a right-ventricular leadless cardiac pacemaker adapted for implantation in electrical contact to a right-ventricular cardiac chamber, the right-ventricular leadless cardiac pacemaker configured to:
 wait for an earliest occurring event of a plurality of events comprising a sensed right-ventricular heartbeat, a sensed communication of at least one pulse marking a heartbeat at an atrial leadless cardiac pacemaker, and timeout of an escape interval;
 respond to the sensed right-ventricular heartbeat by generating at least one pulse by a right-ventricular pulse generator that signals to at least one pacemaker of the plurality of leadless cardiac pacemakers that a right-ventricular heartbeat has occurred and encoding the at least one pulse generated by the right-ventricular pulse generator with a code signifying a right-ventricular location and a sensed event type;
 restart a predetermined right ventricular-to-right ventricular (VV) escape interval after delivering a ventricular pacing pulse after either an atrial ventricular (AV) delay, a ventricular to ventricular (VV) delay, or a ventricular sensed event; and
 respond to timeout of an escape interval by delivering at least one pulse generated by a right ventricular pulse generator, causing a right ventricular heartbeat, and encoding the right ventricular pacing pulse with information designating paced type and right-ventricular location of a right ventricular heartbeat event.

14. The system according to claim 13 wherein:
 the right-ventricular leadless cardiac pacemaker is configured to:
 detect a signal originating from a co-implanted atrial leadless cardiac pacemaker;
 examine an elapsed amount of the ventricular-to-ventricular (VV) escape interval since a most recent right-ventricular heartbeat;
 determine whether the signal originating from the co-implanted atrial leadless cardiac pacemaker is premature;
 in presence of a premature signal, wait for an event with no effect on ventricular pacing;
 in absence of a premature signal, start a right atrium to right ventricular (AV) escape interval that is representative of a typical time from an atrial beat to a right-ventricular beat in sinus rhythm; and
 respond to timeout of the VV escape interval or the AV escape interval by delivering at least one pulse by the right ventricular pulse generator, causing a right ven-

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tricular heartbeat, encoding the at least one pulse generated by the right ventricular pulse generator with information designating paced type and right-ventricular location of a right ventricular heartbeat event, and starting a ventricular-to-ventricular (VV) escape interval and returning to a wait state.

15. The system according to claim 13 wherein:
 the right-ventricular leadless cardiac pacemaker is configured to:
 set the ventricular-to-ventricular (VV) escape interval longer than a predetermined atrial-to-atrial (AA) escape interval to enable backup ventricular pacing at a low rate corresponding to the VV escape interval in case of failure of a triggered signal from a co-implanted atrial leadless cardiac pacemaker.

16. The system according to claim 1 wherein:
 the plurality of leadless cardiac pacemakers comprise a left-ventricular leadless cardiac pacemaker implanted in electrical contact to a left-ventricular cardiac chamber, the left-ventricular leadless cardiac pacemaker configured to:
 wait at the left-ventricular leadless cardiac pacemaker for an earliest occurring event of a plurality of events comprising a sensed communication of a pacing pulse marking a heartbeat at an atrial leadless cardiac pacemaker, and timeout of a left ventricular escape interval; and
 respond to timeout of the left ventricular escape interval by delivering a left ventricular pacing pulse, causing a left ventricular heartbeat, and encoding at least one pulse generated by a left ventricular pulse generator with information designating type and location of a left ventricular heartbeat event.

17. The system according to claim 16 wherein:
 the left-ventricular leadless cardiac pacemaker is configured to:
 detect a signal originating from a co-implanted atrial leadless cardiac pacemaker;
 examine an elapsed amount of the left ventricular escape interval since a most recent left-ventricular heartbeat;
 determine whether the signal originating from the co-implanted atrial leadless cardiac pacemaker is premature;
 in presence of a premature signal, wait for an event with no effect on ventricular pacing;
 in absence of a premature signal, start a left atrium to left ventricular (AV) escape interval that is representative of a typical time from an atrial beat to a left ventricular beat in sinus rhythm; and
 respond to timeout of the AV escape interval by delivering a left ventricular pacing pulse, causing a left ventricular heartbeat, encoding at least one pulse generated by the left ventricular pulse generator with information designating paced type and left ventricular location of a left ventricular heartbeat event, and starting a ventricular-to-ventricular (VV) escape interval and returning to a wait state.

18. The system according to claim 1 further comprising:
 a controller coupled to the at least two pacing electrodes adapted to examine output pulse duration from the at least one pacemaker of the plurality of leadless cardiac pacemakers for usage as a signature for determining triggering information validity and, for a signature arriving within predetermined limits, activating delivery of a pacing pulse following a predetermined delay of zero or more milliseconds, the predetermined delay being determined from a method in a group consisting of preset at

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manufacture, programmed via an external programmer, and adaptively monitoring and conforming to an interval between a prior event of at least one predetermined type and the triggering signal.

19. The system according to claim 1 further comprising:
a controller coupled to the at least two pacing electrodes adapted to examine output pulse waveform from the at least one pacemaker of the plurality of leadless cardiac pacemakers for usage as a signature for determining triggering information validity and, for a signature arriving within predetermined limits, activating delivery of a pacing pulse following a predetermined delay of zero or more milliseconds.
20. The system according to claim 1 wherein:
individual pacemakers of the plurality of leadless cardiac pacemakers are configured for operation in a particular location and a particular functionality at manufacture and/or at programming by an external programmer.
21. The system according to claim 1 wherein:
the plurality of leadless cardiac pacemakers comprise a right ventricular leadless cardiac pacemaker and a left ventricular leadless cardiac pacemaker configured to operate with atrio-ventricular (AV) delays whereby a left ventricular pacing pulse can be delivered before, after, or substantially simultaneously with a right ventricular pacing pulse.
22. The system according to claim 1 wherein:
the plurality of leadless cardiac pacemakers is configured for multi-site pacing that synchronizes depolarization for tachyarrhythmia prevention.
23. The system according to claim 1 wherein:
the at least two leadless pacing electrodes are configured to communicate bidirectionally among the plurality of leadless cardiac pacemakers and transmit data including designated codes for events detected or created by an individual pacemaker wherein data are encoded as pulse width.

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24. The system according to claim 1 wherein:

the at least two leadless pacing electrodes are configured to communicate bidirectionally among the plurality of leadless cardiac pacemakers and transmit data including designated codes for events detected or created by an individual pacemaker wherein data are encoded as binary-coded notches in a pacing pulse.

25. The system according to claim 1 further comprising:
a receiving amplifier/filter adapted for multiple controllable gain settings; and
a processor configured to control gain setting for the receiving amplifier/filter, invoking a low-gain setting for normal operation and detecting presence of a pulse, and invoking a high-gain setting for detecting and decoding information encoded in the detected pulse.
26. The system according to claim 1 further comprising:
the at least two leadless pacing electrodes configured to communicate bidirectionally among the plurality of leadless cardiac pacemakers and transmit data including designated codes for events detected or created by an individual pacemaker wherein data are encoded as modulation of off-time between pulses.
27. The system according to claim 1 further comprising:
a tank capacitor selectively connected to deliver pulses to a pair of the at least two leadless pacing electrodes and adapted for charging and discharging wherein a pacing pulse is generated;
a charge pump circuit coupled to the tank capacitor and adapted for controlling charging of the tank capacitor; and
a processor configured to control recharging of the tank capacitor wherein recharging is discontinued when a battery terminal voltage falls below a predetermined value to ensure sufficient voltage for powering the leadless cardiac pacemaker.

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